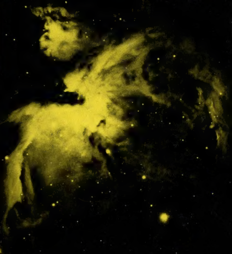
The Variable Star Observer's Handbook

John Glasby



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Sidgwick & Jackson

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'At the moment there is no book written for the amateur astronomer on this important subject, and John Glasby's book will fill a serious gap in the literature.' Patrick Moore

This handbook is the first to provide the astronomy enthusiast with information and news about variable stars. John Glasby describes the many classes of variable stars, and gives the beginner advice on how to recognize them, and what instruments to use. He provides a wealth of information on every aspect of the subject including the calculation of dates of maxima and minima, star charts, magnitude sequences, photographic and photoelectric observations, and the use of the spectroscope. He gives notes and data on the behaviour of certain naked-eye, binocular, and telescopic variable stars during 1970, together with predictions for 1971.

The handbook will be of enormous value to all amateur astronomers regardless of the instruments and equipment at their disposal.

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JOHN GLASBY was born in 1928 at Retford, Nottinghamshire, and was educated at King Edward VI Grammar School and Nottingham University where he graduated with an Honours degree in Chemistry. Since 1952 he has been employed with Imperial Chemical Industries (Nobel) Division where he has carried out research on detonators and rocket propellants. At present he is in charge of the spectroscopy group doing research in infra-red and nuclear magnetic resonance studies.

In 1958 he joined the Variable Star Section of the British Astronomical Association, being appointed Director in January 1965. He was elected a Fellow of the Royal Astronomical Society in 1960 and has published *Variable Stars* in 1968 and *The Dwarf Novae* in 1970. Other interests, apart from Astronomy, include writing fiction and his books have been published both in this country and the United States.

THE

Variable Star Observer's Handbook

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Contents

Editorial Note

Abbreviations are used for societies as follows:

A.A.V.S.O. = American Association Variable Star Observers.

B.A.A. = British Astronomical Association.

I.A.U. = International Astronomical Union.

V.S.S.B.A.A. = Variable Star Section of British Astronomical Association.

Preface

The study of variable stars may be said to have begun with the discovery of the long-period variable Mira (*o* Ceti) by Fabricius in 1596, although there are some who would say that it began even earlier in 1572 when Tycho Brahe commenced systematic observations of the brilliant galactic supernova which appeared in the constellation of Cassiopeia. For almost three centuries, however, the number of known variable stars remained very small and observations of their light changes were, at best, sporadic. In 1855 Argelander and his colleagues at the Bonn Observatory prepared their great atlas of the northern heavens – the Bonner Dürchmusterung – on which were plotted the accurate positions of the stars down to a limit of about ninth magnitude. With this as a guide, observers systematically searched the heavens for stars which were either not recorded or were of a different brightness to that given in the atlas. Such stars were then rigorously followed for several weeks in order to determine any change in their brightness.

At about the same time, photography came to the aid of the astronomer enabling hundreds of stars to be photographed on the same plate. Examination of plates taken of the same region over a period of time resulted in the discovery of many more variables than had hitherto been known. At the present time some 20,000 variables have been discovered and many more are added to the list each year.

Throughout the whole history of variable star observation the amateur, using only modest equipment, has been well to the forefront and most of the early discoveries were made by such men. There are, of course, certain fields in which the amateur can play only a minor role. The study of very faint stars is naturally limited to those observers having large telescopes at their disposal. Photoelectric estimates of small, rapid changes in brightness require sophisticated equipment not normally found in amateur hands.

Similarly, spectroscopic work is best carried out by the professional astronomer having access to this rather refined technique.

This is all quite understandable but provided the amateur recognizes his limitations in this respect there still remains an enormous amount of valuable work which may be done. The time available on the large telescopes in the professional observatories is severely limited and such instruments are best reserved for the kind of work which they alone can do. The task of following the light variations of many types of variable stars falls mainly upon the shoulders of the amateur.

In recent years the spectacular advances in rocketry and space research have resulted in a vast increase in our knowledge of the lunar surface and conditions on both Venus and Mars and it seems inevitable that planetary observation will be taken over more and more by manned and unmanned space probes. Almost certainly this will mean a reduction in the work carried out by terrestrial observers. Such a case does not apply to the stellar observer. It will be many decades, perhaps centuries, before even the nearest star is reached and the continuing need for observations of variable stars will go on for as long as can be foreseen.

The main theme of this book lies in an attempt to cover most facets of variable star observing both for the beginner and the more advanced observer. The reader will find charts and sequences of comparison stars in the Appendix. These have been so chosen as to cover the widest possible range of instruments from naked-eye variables to those requiring telescopes with apertures of twelve inches or more. The use of these charts is fully explained in the text and it is hoped that they may stimulate as yet uncommitted readers to take up this extremely interesting and important branch of astronomy. Although the metric system is now being increasingly used, apertures have been given in inches as at present this provides the reader with a clearer idea of size than the use of centimetres.

It is a great pleasure to thank my many colleagues in the Variable Star Section of the British Astronomical Association with whom I have collaborated for many years, and in doing so would seriously advise all interested readers to join the Section as much more can be accomplished on a communal basis than working in isolation.

Stevenston, Scotland. J.S.G.
November, 1970

CHAPTER 1

Astronomical Instruments and Their Use

Although there are a few variable stars which are visible to the naked eye throughout the whole of their light cycles, the vast majority require some form of instrumental aid to follow their variations in brightness satisfactorily. In this chapter we shall be discussing the various instruments used by observers ranging from binoculars and small telescopes to the more sophisticated photographic and photoelectric techniques used by the advanced observer. As the observer becomes more proficient, he will naturally wish to extend his observations to those classes of variable which require larger and more refined instruments – and it is essential that he should know the limitations of the various types of telescope – and those which are best suited for the kind of observing he wishes to undertake.

TELESCOPES AND OBSERVATORIES

Basically, there are two types of telescope, the refractor and the reflector. Both varieties are rated according to their aperture which is the clear diameter of the object glass in the refractor or of the mirror in the reflector. The larger the diameter, the fainter are the stars which can be seen. Before going on to consider the design and relative merits of the two types it is worthwhile mentioning the three basic functions of a telescope, particularly since some confusion often arises over the meaning of the terms 'magnification', 'light grasp', and 'resolving power'.

1. The magnifying power of a telescope depends solely upon the focal lengths of the object glass or mirror and that of the eyepiece, being given by the following formula:

$$M=F/f \qquad (1)$$

where M is the magnification in diameters, F is the focal length of the object glass or mirror and f is the focal length of the eyepiece.

It will be seen that the aperture of the telescope plays no part in determining the magnification. For variable star observation it is advisable to use two or three eyepieces of different focal length – a low-power one giving a wide field and magnifying ten times per inch of aperture, a medium-power eyepiece with a magnification of thirty times per inch of aperture, and a high-power one magnifying sixty times to each inch of aperture.

Increasing the magnification has both advantages and disadvantages. Very often it will be found to darken the background and enable faint stars at the very limit of detection to be observed more easily. On the other hand, a higher magnification results in a reduction in the size of the field of view and any atmospheric disturbances as well as small vibrations of the telescope mounting are also magnified. When no driving clock is used it will be found that the stars move more quickly across the field when high powers are employed. The extreme limit of useful power is claimed to be one hundred times the aperture of the instrument measured in inches, but this should be used only on very close double stars, and then only when seeing conditions are very good and the optics of the telescope are of the highest quality.

2. As its name implies, the light grasp of a telescope is a measure of the amount of light which it gathers and, unlike the magnifying power, this depends entirely upon the aperture. Theoretically, this is proportional to the square of the diameter of the objective but where refractors are concerned it falls off rather rapidly in practice with increasing aperture due to absorption of light by the material of the lens itself. The theoretical limiting magnitude of a telescope is another way of defining the light grasp and is the magnitude of the faintest star which could be seen under ideal observing conditions and with perfect optics.

Since such conditions are rarely, if ever, encountered, the limiting magnitude will, in practice, depend upon several factors including the presence of moonlight, haze, atmospheric absorption, and any slight defects in the optical system of the instrument. The acuteness of the observer's vision must also be taken into account. As a rough guide a 3-inch telescope will show stars down to 11·5 magnitude; a 6-inch down to 13·0 magnitude and a 12-inch down to 15·0 magnitude under good conditions.

3. The resolving power of a telescope must be clearly distinguished from its magnification, being proportional to the

aperture and the effective wavelength of light. Briefly, the resolving power is a measure of the ability of the telescope to separate two very close stars. Whenever light passes through an aperture such as that of a telescope objective, the rays of light spread out slightly owing to diffraction. This results in the star images appearing, not as points of light, but as discs surrounded by a series of rings. The images of two very close stars will therefore overlap and simply increasing the magnification will not result in any separation of the two discs. This may only be done by increasing the aperture. The resolving power of an instrument is therefore given by the angular separation of a close double star, the two components of which can just be separated, being given by the following equation:

$$R = 5''/d \qquad (2)$$

where R is the angular separation of the centres of the two images in seconds of arc and d is the aperture of the telescope in inches.

Again, we find that in practice the resolving power often falls far short of the theoretical value due mainly to eddy currents in the atmosphere and as one may expect this effect is most pronounced at sea level. For this reason, most of the major observatories are built as far above sea level as possible.

The refracting telescope was the first to be invented, about 1609, and consists in principle of two lenses. The larger of the two and the one having the greater focal length is known as the objective, the smaller being termed the ocular or eyepiece. The earlier telescopes suffered from several defects, the most troublesome being known as chromatic aberration. A simple objective lens does not bring the rays of light of different colours to the same focus, red light being brought to a focus nearer the eye than blue light with light of the other colours having foci intermediate between these points. Since the eye is most sensitive to yellow light, the image of a star will appear as a yellowish disc surrounded by a bluish halo. One way of overcoming this defect is to increase the focal length of the objective but such instruments are both long and cumbersome. The difficulty was finally resolved by the use of a compound lens consisting of a converging lens of crown glass and a diverging lens of flint glass. The opposite chromatic aberrations of the two components are adjusted to nullify each other (Fig. 1).

In the reflecting telescope, the light is collected by a concave mirror and since the light rays are reflected and not refracted, there is no chromatic aberration with a reflector. Both refractors

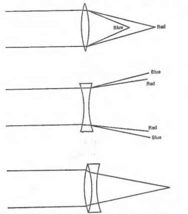


Fig. 1. *The combination of a convex and concave lens eliminates chromatic aberration and brings the rays of all colours to a common focus*

and reflectors, however, do suffer from spherical aberration. This is similar to chromatic aberration but in this case is due to the fact that spherical surfaces do not bring parallel rays of light to the same focus. By using specially ground lenses, which are, however, expensive, this may be overcome in a refractor. In a reflecting telescope it is usually done by using a parabolic mirror in place of a spherical one. This is comparatively simple to do for small reflectors, but in the larger instruments a special correcting lens is inserted just in front of the principal focus.

There are several different types of reflecting telescopes, in all of which the light is brought to a focus inside the tube. The very large reflectors such as the 200-inch Hale telescope at Mount Palomar are known as direct-focus instruments. The observer actually sits inside a small cage situated at the prime focus and although this inevitably results in some of the incoming light being obstructed, this is insignificant in comparison with the total light collected. In smaller reflectors, of course, this is not possible and the image is brought to a focus either by means of a small plane mirror inclined at 45° just inside the principal focus, as in the Newtonian form (Fig. 2), or by the use of a small convex mirror at the same point which diverts the light back down the tube and through a small hole in the mirror (Fig. 3). The Cassegrain reflector as this is called has two advantages over the Newtonian. It enables the observer to observe at the lower end of the instrument and for a given size it has a focal length about three times that of the Newtonian.

Another type of reflector which overcomes the difficulty of spherical aberration was developed in 1930 and is known as the Schmidt camera. This instrument employs a spherical mirror and a very thin correcting plate which introduces no chromatic aberration (Fig. 4).

Strictly speaking, this instrument is not a telescope since it cannot normally be used for visual observation. The image is brought to a focus on a curved plate over which the photographic film is placed. Numerous Schmidt cameras are now in operation all over the world and are used for photographic surveys of large areas of the heavens. One important characteristic of these instruments is that the star images are in sharp focus right to the edge of the field whereas in the conventional instruments, the usable field diminishes as the aperture is increased due to an effect known as coma. Here the images which are situated far from the optical axis are elongated into small patches of light resembling a comet.

Coma is completely absent in the Schmidt camera and also in the Bouwers-Maksutov camera which is a modification of the Schmidt system. Here the aspherical correcting lens is replaced by a miniscus lens with curved surfaces, this also serving to correct the spherical aberration of the spherical mirror.

Both refractors and reflectors have their respective advantages and disadvantages. Since the refractor is essentially a closed optical system, the images tend to be steadier than those in a reflector. Very often, the temperature of the air inside a reflector

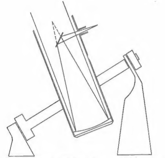


Fig. 2. *Newtonian reflector on an equatorial mount*

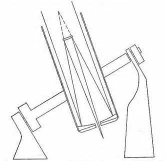


Fig. 3. *Cassegrain reflector on an equatorial mount*

tube differs from that outside with the result that eddy currents form which can seriously distort the image. This can be overcome to a certain extent by the use of an open tube although here there is the danger of extraneous light reaching the mirror. In this respect alone, a small refractor often performs better than a reflector of comparable size.

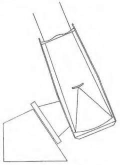


Fig. 4. *The Schmidt camera*

With very large apertures, this advantage which the refractor possesses is outweighed by other problems which arise. We have already mentioned one of these, namely that the thickness of the object glass (which usually increases in step with the aperture) results in more and more light being absorbed by the glass. Another advantage of the large reflector is that since the light does not have to pass through the mirror but is merely reflected from a thin layer of silver or aluminium, the material of which the mirror is constructed need not be of high quality glass. In addition, the mirror does not have to be supported solely by its edges as does a lens.

Coming now to the question of eyepieces, these are of two types known as positive and negative eyepieces In the positive type the image is formed between the objective and the eyepiece and consequently it may be used in conjunction with a micrometer. A negative eyepiece cannot be used in this way since the image is formed inside the lens. For very high powers a special eyepiece consisting of only a single lens may be used, but in general the eyepiece is made up of two lenses known as the field lens (farthest from the eye) and the eye lens. All astronomical eyepieces give an inverted image unless used with a Gregorian telescope but as this practice is universal it proves to be no disadvantage. To form an erect image would require the use of additional lenses or prisms, all of which reduce the amount of available light. Several varieties of eyepiece exist, among which the following may be mentioned:

Orthoscopic. This positive eyepiece consists of a triple field lens and a single eye lens and gives a very flat field free from distortion around the edges. For this reason it is especially useful for high powers.

Huygenian. Most common lenses are of this type which usually consists of two plano-convex lenses with their plane faces towards the eye. Although a negative eyepiece it is possible to place cross-wires inside the tube at the focus of the eye lens when it proves very useful as a guiding eyepiece for astrophotography.

Ramsden. This eyepiece, like the Huygenian, also consists of two plano-convex lenses but in this case the plane surfaces face outward. The field is generally flatter than with the previous type.

Monocentric. This eyepiece is made up of a triple lens system and is a useful one for variable star work in that it gives very good definition although it does have the disadvantage that the field of view is relatively small.

Kellner. This positive eyepiece has a convex or sometimes a plano-convex field lens, the eye lens being an achromatic plano-convex lens. The field of view is normally quite large and flat and a Kellner eyepiece is most useful for low powers when finding the field of a variable star.

Erfle. This eyepiece consists of six elements and gives very good definition when well made. There is a slight loss of light due to the number of lenses but it performs well in the observation of variable stars and can be recommended for this purpose.

Barlow. The Barlow lens consists of a concave, or concave-miniscus, lens with a negative focal length which is placed between the objective and the eyepiece. The result is an effective increase in the focal length of the objective, virtually doubling the magnification. Such a lens is most useful for lunar and planetary observation but as far as variable-star work is concerned there is a tendency to form 'ghost' images and the inevitable light loss makes it unsuitable for satisfactory observation particularly of faint stars.

Large telescopes are usually fitted with small telescopes known as 'finders' mounted on the main tube and adjusted by means of screws so as to be accurately parallel with it. By means of these 'finders' the star may be centred so as to be visible in the much more limited field of the main instrument.

The telescope itself, of course, must be mounted. If the observer wishes to take long-exposure photographs of various star fields it is essential that, for satisfactory results, the mounting should be of the equatorial type. There are several different types of equatorial mounting but all have certain features in common – a polar axis which points accurately to the celestial North (or in the southern hemisphere the South Pole and a declination axis perpendicular to it. The telescope itself is mounted on the declination axis and consequently it can be made to follow a star by a single movement only, about the polar axis.

It will readily be seen that this is of particular advantage where celestial photography is concerned. Where there is no driving clock fitted to the telescope, the telescope may be made to follow the stars quite accurately by moving it smoothly in one direction, keeping a guide star aligned on the crosswires in the finder. Very often it will be found helpful to place this star out of focus, it being easier to keep an extended image aligned on the crosswires. A more accurate and less tedious method is by the use of a driving clock which may be either weight-driven or use an electric motor. In either case the drive is transmitted to the telescope via a large toothed wheel on the polar axis which is turned slowly and smoothly by means of an endless worm.

For purely visual work, an equatorial mounting is not a necessity and the altazimuth stand, provided it is secure and free from vibration, is quite satisfactory. The pillar-and-claw stand which is sometimes found used with small refractors is not recommended since it is virtually impossible to eliminate vibration with such a mounting.

Small telescopes, for example a 3-inch refractor or a 4-inch reflector, are generally sufficiently portable for them to be erected and dismantled during each observing session, especially if they are mounted on an altazimuth stand. Larger instruments require to be permanently mounted and this implies some form of observatory to protect the observer from the elements and also to act as a shield against extraneous light sources. For lunar and planetary work, it is possible to build a substantial site equipped with a dome but this can be expensive. For variable star work, a dome is not only unnecessary but can sometimes be a hindrance. In a single night an observer can make estimates of the brightness of between thirty and forty variables depending upon his experience and these will be situated in all parts of the sky. Unless the sky is perfectly clear, scattered cloud will necessitate moving the telescope fairly quickly from one region to another and this will prove difficult if the observatory is equipped with a moveable dome.

The simplest and most inexpensive form of observatory under these conditions is the run-off shed where the entire shed with the exception of one upright is moved on wheels to leave the telescope in the open. Provided the shed is moved ten minutes or so before the observing session begins there will be little, if any, trouble from circulating air currents as are so often found in a virtually enclosed space. It should be mentioned here that for the most accurate results, no form of heating should be used near the telescope.

Binoculars

A pair of binoculars are extremely useful for observing variable stars. As we shall see in Chapter 5 there are many variables which may be followed throughout the whole of their light cycles by means of binoculars alone and a very large number of the long-period variables are sufficiently bright at maximum to require binoculars for their observation at this phase rather than a telescope.

Binoculars are graded according to their magnification and the diameter of the object glass in millimetres. For example 7×50 binoculars have a magnification of seven diameters and object glasses which are fifty millimetres in diameter. For most variable star work, 8×30, 7×50 and 12×40 instruments are eminently suitable. Such binoculars will enable the observer to see down to between eighth and ninth magnitude on a clear, moonless night. Since the light-gathering power, and hence the limiting magnitude, is dependent upon the clear aperture, larger binoculars, for example 15×70 and 16×60, will go down to about tenth magnitude under similar conditions.

Whatever their size, it is essential that binoculars should have a firm support for variable star work. It is virtually impossible to make a satisfactory estimate of brightness with hand-held binoculars as the star images will be far from stationary in the field of view.

Photographic Equipment

Many amateur observers are now turning their attention to photographic work and with the increasing availability of orthochromatic and panchromatic films and suitable filters it is almost as easy to take stellar photographs on a scale closely approximating the photovisual as it is to take an ordinary photograph without the necessary filter. The use of photography in variable star work is fully described in Chapter 9 and here we shall deal only with the choice of camera and its accessories.

Ideally, a half-plate or whole-plate camera will provide the most accurate results for several reasons. Unlike films which can stretch to an indeterminable amount, glass forms a very rigid base which eliminates distortion almost completely. The use of much larger negatives also means that generally more detail can be seen, especially on whole-plate negatives. The ability to focus the field on a ground glass plate before insertion of the photographic plate is also a real advantage. Although pleasing results can often be obtained simply by mounting the camera on the telescope tube thereby obtaining photographs of very wide fields, these have limited value in variable-star work. We require photographs of much smaller fields with as faint a limiting magnitude as possible for serious study.

This entails not only making long exposures of the order of twenty minutes and longer but also the use of focal plane photography with the plate or film positioned at the focus of the telescope. In other words, we are using the telescope itself as a camera. The obvious disadvantages of a plate camera are its bulkiness and the relatively high cost both of the camera itself and the plates themselves.

For this reason, most amateurs prefer to use 35-mm. single lens reflex cameras which are comparatively small, light, and inexpensive. As the field is viewed through the lens, any necessary

adjustments may be made just prior to making the exposure. The small size of the negative means that enlargement is always necessary.

In order to obtain photovisual magnitudes, a yellow filter is necessary. For the most accurate results a narrow-pass Scott filter may be used but the less expensive and more readily obtainable Wratten No. 8 yellow filter produces images which are sufficiently close to photovisual magnitudes for most purposes. Inevitably, of course, a filter will absorb some light but with long exposures this is negligible.

CHAPTER 2

The Family of Variable Stars

Many thousands of stars are known whose brightness does not remain constant but varies with time. Some vary by only a small amount so that very sensitive photoelectric equipment is necessary to measure the extremely small changes in brightness while others are more than 100,000 times brighter when at maximum than at minimum. Some stars are so erratic in their variability that it has so far proved impossible to find any underlying pattern at all to their behaviour. A much larger number, though, exhibit a regularity in their light variations which enables us to define some sort of period from one maximum to the next. This period may be remarkably constant as in the case of the Cepheids and eclipsing variables or it may vary quite appreciably between successive maxima as found in the long-period and semi-regular variables.

Quite clearly then the family of variable stars is made up of several different classes and from numerous observations made over the course of three centuries or so we can now classify them into a number of well-defined types according to the mechanism of their light variation. We must not overlook the fact too that the spectra as well as the luminosity of these stars also vary but more will be said about this later.

The Designation of Variable Stars

Before we go on to consider these various types of variable star it is important that we should know how they are designated. In the middle of the nineteenth century, the systematic study of these stars was begun, mainly at the instigation of Argelander, and it was soon appreciated that some means of distinguishing them from other, non-variable, stars was required. Accordingly, it was universally agreed that the capital Roman letters should be reserved for these stars, followed by the name of the constellation as usual. Unfortunately the letters from A to Q had already been used for certain non-variable stars in the newly charted southern

constellations. For this reason the first variable to be discovered in any constellation is given the letter R followed by S, T and so on to Z. When further letters are needed, the series recommences with RR, RS, RT to RZ; SS, ST to SZ; TT, TU to TZ and so on until ZZ is reached. The nomenclature then continues with AA, AB to AZ followed by BB, BC to BZ, finally ending with QZ.

All in all, this will give us 334 different combinations. It will be noticed that where two letters are used, the second is always later in the alphabet than the first. For example, we do not have such combinations as NM or QP. To avoid confusion, the letter J is omitted. Where more than 334 variables are discovered in any constellation, the series then goes on with V335, V336 and so on for as long as is necessary. There are, of course, certain very bright variables which were catalogued by Bayer in the seventeenth century and these have retained the Greek letters originally assigned to them. Among such stars are γ Cassiopeiae, o Ceti, β Lyrae and β Persei.

There are some twenty-five different types of variable stars but we may conveniently divide them into three broad groups – (1) *the eclipsing variables*, (2) *the pulsating stars*, and (3) *the eruptive variables*. In general, it is true to say that we may distinguish between the various classes simply from a study of their light variations. Only in certain borderline cases do we require recourse to their spectra. The spectroscopic changes which take place are more useful when we come to investigate the actual physical changes going on within the star which give rise to the observed variations in brightness.

The Eclipsing Variables

Let us first examine the very large group of stars in which the light variations are not due to any physical change inside the star itself. These are generally known as the extrinsic variables for this reason. The first star of this kind to be discovered was Algol (β Persei). In 1669, Montanari detected the abrupt decreases in the brightness of this second magnitude star although a further century was to elapse before their periodicity was recognized by Goodricke in 1782. It is to Goodricke, too, that we owe the correct explanation of the regular light changes of this particular variable.

If we draw a graph showing how the observed brightness changes over a period of time we obtain what is known as the light curve of a variable star. The light curve of Algol is shown in Fig. 5 and

it will readily be seen that the light variations are completely unlike those of Mira (Fig. 19) which is the prototype of another class of variable (the long-period variables). Goodricke argued that in the case of Algol we have not one, but two stars of unequal luminosity revolving around a common centre of gravity, the orbital plane being such that it lies in our line of sight as seen from Earth. This being so, the two stars will mutually eclipse each other twice in each revolution.

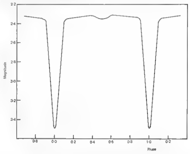


Fig. 5. *Light curve of Algol (β Persei)*

When the darker star passes in front of the brighter companion, the total brightness of the system diminishes quite considerably and gives rise to the primary minimum in the light curve. Half a revolution later, the positions of the two stars are reversed and there is only a slight decrease in luminosity resulting in the much shallower secondary minimum.

In spite of the admirable way in which this idea explained the observed changes in brightness, it was not possible to prove it at the time. Even in the most powerful telescopes, Algol appears only as a single point of light with no evidence at all of any duplicity. It was not until the invention of the spectroscope which clearly

demonstrates, as we shall see, that here we have two stars in motion about each other that the final proof came. It should perhaps be mentioned here that many other stars are known in which there is no detectable change in brightness although the spectroscope reveals that they are binaries. It is only when the plane of the orbit lies close to our line of sight that any eclipses can occur.

Several hundred stars similar to Algol are known, all having light curves which are very much alike. In all of them the maxima are virtually flat, certain small deviations being due to the fact that the fainter star re-emits some of the light it receives from the primary. This reflection effect means that the amount of light which the fainter, secondary component contributes to the total varies slightly depending upon whether the darker or the brighter hemisphere of this star is facing us. The former occurs around the time of primary minimum and the latter around secondary minimum. This may be seen quite clearly from Fig. 6.

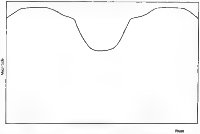


Fig. 6. *Enlarged portion of the maximum of an Algol variable showing the reflection effect*

In addition to the numerous Algol variables, there is a second large class of eclipsing variables whose prototype is the third magnitude star β Lyrae. Here we find from an inspection of the light curve that the light variations are continuous. There is no

relatively flat portion at maximum brightness. Fig. 7 shows also that the secondary minimum is generally more pronounced than that in many of the Algol stars.

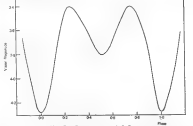


Fig. 7. *Light curve of β Lyrae*

Clearly there is some secondary cause here which results in such rounded maxima. This characteristic is attributed to the comparatively small separation of the two components within these systems. In stars such as Algol, the two bodies are sufficiently well separated for the individual stars to be more or less spherical in shape. In the β Lyrae variables, however, the stars are so close together that the powerful gravitational and tidal forces generated deform them into ellipsoids. As a result we not only have the light variations produced by the eclipses but also by the varying surface areas of the stars presented to us. We may regard such stars as being very closely locked together by strong gravitational ties and, like the Earth-Moon system, they always turn the same face towards each other apart from a very small vibration effect. A further complication exists in the β Lyrae variables, namely the presence of a stream of high-temperature gas flowing from the primary to the secondary.

Many Algol stars, too, are known in which a gas stream exists and perhaps the first of all in which this was discovered was

RW Tauri which consists of a white B9e star and a cooler, yellow companion of spectral class KO. From a spectroscopic study of this variable, Joy discovered that the emission lines of hydrogen in the spectrum of the primary behave in an extremely puzzling manner. At the beginning of the eclipse they are displaced towards

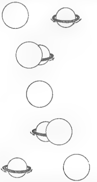


Fig. 8. *RW Tauri; an eclipsing variable with a luminous gas stream in the system*

the red end of the spectrum while immediately after eclipse they are shifted by the same amount towards the violet. During eclipse they disappear altogether. Since it is only the emission lines of hydrogen which are affected in this strange way, Joy concluded that they originate in a luminous ring of hydrogen gas surrounding the white star (Fig. 8).

The stars which make up the Algol and the β Lyrae variables are almost invariably very much larger than the Sun. However, some eclipsing variables are known in which both components are red dwarfs with sizes and masses closely approximating those of the Sun. The first such variable to be discovered was an insignificant star of the eighth magnitude now known as W Ursae Majoris. Like the β Lyrae variables, the light curves of these stars show a continuous variation (Fig. 9) but since the two components are so similar in size and surface brightness, the primary and secondary minima are almost identical. The stars in these binary systems are so close together that not only are their periods extremely short, only a matter of a few hours, but they actually seem to be in contact. When we come to discuss the dwarf novae later in the chapter, we shall see that the W Ursae Majoris variables are considered by many astronomers to be the precursors of these eruptive variables.

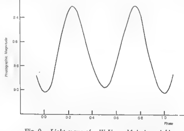


Fig. 9. *Light curve of a W Ursae Majoris variable*

There are, in addition to the above, certain close binary stars in which the components are so distorted by gravitational forces that, even though the orbital plane is orientated too high for any eclipses to occur, their light varies by a small amount due to the continuously changing surface area which is presented to us.

ζ Andromedae and δ Cassiopeiae are examples of these so-called ellipsoidal variables.

When we consider the wide range of sizes and temperatures found among the stars it is inevitable that within the large class of eclipsing variables we should find some rather bizarre systems.

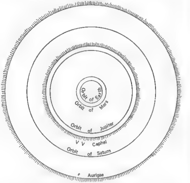


Fig. 10. *Dimensions of two supergiant stars with the planetary orbits*

VV Cephei and ε Aurigae, for example, both consist of a colossal supergiant star of extremely low density and a far smaller, brighter companion. The M2-type star in the VV Cephei system has a diameter 1,200 times greater than the Sun, while the K3 star in the ε Aurigae system is even larger and if it were in the position of the Sun it would extend far beyond the orbit of Saturn as shown in Fig. 10.

As we might expect from stars of these enormous dimensions, the periods of VV Cephei and ε Aurigae are very long indeed, being 7,430 and 9,883 days respectively. The next primary eclipse of VV Cephei is not due until August 1977 and that of ε Aurigae will occur in June 1983. Being relatively infrequent occurrences, these eclipses are closely studied by astronomers whenever they take place. Since the outer atmospheric levels of these supergiants are so tenuous, the light of the bright stars shines through them for part of the eclipse and we are able to tell, from spectroscopic studies, a great deal about the physical and chemical constitution of their atmospheres, information it would be almost impossible to obtain by any other means.

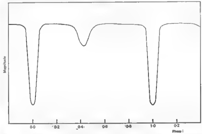


Fig. 11. *Displacement of the secondary minimum in an eclipsing variable indicative of an elliptical orbit*

If we consider only the light curves of these eclipsing variables, we may derive quite a lot of information about them. To illustrate this let us take another look at the light curve of Algol (Fig. 5). It will be seen that the shallow, secondary minimum comes almost midway between the primary minima. This tells us at once that the orbit is approximately circular. In other variables of this kind the secondary minimum lies closer to one of the primary minima than the other (Fig. 11). Here the orbit is elliptical and from the relative

displacements we can calculate the orbital eccentricity with a fair degree of accuracy.

From the depths of the primary and secondary minima we may also determine the relative luminosities of the two components. In the simplest case of all where we have two stars of almost equal brightness (a condition which is only rarely met with in this type of variable), both primary and secondary minima will be of equal depth since, irrespective of which star eclipses the other, the total light of the system will be reduced by the same amount. Let us take another example. Suppose that we have a system of the Algol type in which one star is only a quarter as bright as the other. Then when the fainter star eclipses the brighter companion, we receive only a quarter of the light which reaches us when they are both side by side. Conversely, when the fainter star is in eclipse, we receive three quarters of the total light. The depths of the primary and secondary minima will therefore be in the ratio of 3:1.

Now it is important at this point to bear in mind that this will only be the case where the eclipses are total. If they are either partial or annular, the above simple relationship does not hold. Fortunately the light curve provides us with the clue to the nature of the eclipses. A partial eclipse will occur if the orbital plane does not coincide with the line of sight as seen from Earth. Similarly, if the orbital plane is exactly in the line of sight but one component is much smaller than the other, the eclipse will be annular.

When either of these events takes place, the secondary minimum will be comparatively flat at the base rather than sharply pointed – this indeed being so for Algol itself where the eclipse is partial. Since the brighter companion is usually the smaller of the two, this effect is normally more pronounced in the secondary minimum. The primary minimum, though, often shows a slight broadening at the base where there is inequality in the diameters of the components since then the eclipse lasts slightly longer than when both stars are of approximately equal size.

We can also discover something about the temperature of the two stars from the light curve. Undoubtedly the most accurate means of determining the surface temperature is from the spectrum but quite often we find that only the spectrum of the brighter component is visible and we cannot directly determine the surface temperature of the fainter star in this case by spectroscopic methods. This can only be done by observing the eclipse through special colour filters. The three standard filters normally used are those which let through the ultraviolet, blue, and yellow regions of

the spectrum. This is normally known as the UBV system (brightnesses measured with a yellow filter correspond very closely to visual ones).

If one star has a higher surface temperature than the other it will emit more radiation in the blue and ultraviolet regions and if this star is being eclipsed by the fainter (and therefore yellower)

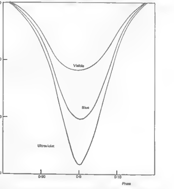


Fig. 12. *Three-colour light curves of an eclipsing variable*

companion, the minimum as measured in blue or ultraviolet light will be deeper than that measured in yellow light. This effect is clearly shown in Fig. 12.

Apsidal Rotation

Mention has already been made of those stars in which the ellipticity of the orbit results in the secondary minimum being displaced towards one of the primary minima. In some eclipsing

variables we find a similar state of affairs but here the position of the secondary minimum shifts with time relative to the primary minima. This periodic motion is of particular interest in the study of these variables since it allows us to obtain valuable information concerning the interiors of the individual stars which we would otherwise be unable to obtain.

This feature is known as apsidal rotation and is due to the major axis of the orbit itself turning through a complete revolution over a period of time. Such a situation is shown diagrammatically in Fig. 13.

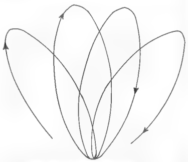


Fig. 13. *Open orbit of a close binary system showing apsidal rotation*

Basically this aspidal rotation is caused by the elliptical orbit not being closed and naturally the time taken for one complete revolution is equal to many hundreds of orbital revolutions of the two stars themselves. The reasons why the orbit is not completely closed are quite complex. Mainly, though, it is because one of three conditions prevails within the system.

1. If there is a third body sufficiently close for its gravitational field to produce an appreciable effect on the two stars, this will result in the common centre of gravity no longer acting as a point source. One very well-known instance of this is the apsidal motion of the Moon about the Earth due to the external influence of the Sun.

2. In the absence of any outside influence, it may be that in the equations which we use to describe the motions of the two stars, one of the terms is not constant but variable. Again we have a good example of this in the Solar System. The slow change in the perihelion of the planet Mercury can only be explained in terms of Einstein's Theory of Relativity and not according to the simpler Newtonian mechanics.

3. Finally, apsidal motion may be brought about if one or both of the stars is appreciably distorted from a spherical shape. It is in this particular case that we can learn a lot about the internal constitution of these stars. It is possible then, by means of a complicated method, to determine how the density within the star varies with depth.

Where we are able to supplement the light curves with spectroscopic information, many more characteristics of these eclipsing variables may be derived. In quite a number of cases the spectrum due to each component is visible so that we are able to tell the spectral classes of the individual stars. We are also able to measure the velocities with which the components are moving in their orbits from the Doppler effect.

The Doppler Effect

This has such a tremendous application in many fields of astronomy and in particular in the study of variable stars that it is worth while here to mention it in some detail. Most of us are familiar with the Doppler effect where sound waves are concerned. When an express train passes non-stop through a railway station sounding its whistle continuously, the pitch rises as the train approaches the observer and falls as it moves away. Since, when approaching, the distance between the source and the observer is diminishing, the sound waves become more compressed resulting in a rise in pitch, the opposite effect taking place when the source is receding. Doppler, who noted this in 1842, suggested

that there should be an analogous effect with light waves and thought that the colour of a star should be noticeably altered due to its velocity towards or away from us. Unfortunately, the velocities of the stars are so small compared with that of light itself that no perceptible changes in colour can be distinguished.

It remained for Fizeau to show that the effect should be detectable by the shift in the spectral lines whose positions can be measured extremely accurately. The expression used to calculate such shifts in the spectral lines due to the Doppler effect is:

$$\lambda_1 = \lambda_0(1 + V/c) \qquad (1)$$

where λ_1 is the wavelength of the displaced line, λ_0 is the true wavelength measured in the laboratory when both source and observer are at rest with respect to each other, V is the velocity of approach or recession and c is the velocity of light. If the source is receding from us the radial velocity (V) is said to be positive and if it is approaching us, it is negative.

As may be seen from the above equation, a velocity of recession will produce an increase in the wavelength, that is, a displacement towards the red end of the spectrum, while a velocity of approach will result in a shifting of the lines towards the blue end.

In the case of a binary system, therefore, when the stars are in eclipse there will be no Doppler shift of the lines in the spectrum since at this point in their orbit they are neither approaching nor receding from us. When the variable is at maximum brightness, however, one will be receding while the other will be approaching. Consequently, the lines in the spectrum will appear double and by measuring the Doppler shift of each component we can determine, quite accurately, their radial velocities.

If then we now plot these velocities as a function of time (rather in the same way as the light curve), we obtain the radial velocity curve of the variable. That of a typical Algol variable is shown in Fig. 14.

One important feature of the radial velocity curves is that they enable us to determine the eccentricity of the orbits of these variables with a high degree of accuracy. If the radial velocity curve is symmetrical, the orbit is a circular one. If, on the other hand, it is asymmetrical, the orbit is an ellipse and from the degree of asymmetry, we may calculate the eccentricity.

Quite clearly, once we know the velocities of the two stars we may work out the circumference, and hence the diameter, of the orbit simply from a knowledge of the period. The light curve also

tells us the duration of each eclipse and combining this with the orbital velocity, we immediately obtain the diameters of the component stars. Even this, however, does not exhaust the information we can get from these stars. In those cases where the orbit is circular, or where the spectra of both stars can be observed, we may compare the Doppler shift of one set of lines with the other and thereby obtain the relative distances of the stars from their common centre of gravity.

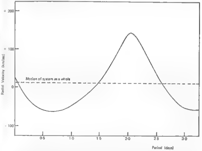


Fig. 14. *Radial velocity curve of a typical Algol variable*

The lines in the spectrum, too, provide a wealth of information. U Cephei, for instance, has a spectrum in which the absorption lines of calcium, helium, and magnesium due to the B8-type star are abnormally broad and diffuse. When this star is partially eclipsed by its companion, the lines become markedly distorted. This effect is well known and clearly understood by astronomers being due to the rapid rotation of the star on its axis.

We must not forget either that the two stars are bound together by gravity and that both Newton's and Kepler's laws hold in these systems just as they do within the Solar System. Using the data already obtained we may derive the masses of the two stars in the

following way. The total mass of a binary star system is found by means of the equation:

$$m_1 + m_2 = A^3/P^2 \qquad (2)$$

where m_1 and m_2 are the individual masses of the two stars in terms of the mass of the Sun. A is the semi major axis (one-half the length of the longer axis of the ellipse measured in astronomical units) and P is the orbital period in years.

From the light curve and the shift of the lines in the spectrum we are able to plot the motion of each star around the common centre of gravity and the ratio of the larger orbit to the smaller is also the ratio of the masses of the individual stars. From this ratio and the total mass, it is a simple matter to determine the individual masses.

Table 1
ECLIPSING VARIABLES

Star	*Magnitude* *Max*	*Min I*	*Min II*	*Period (days)*	*Spectrum*	*Type*
TW And	8·85	11·10	9·01	4·112745	dF0+G6	Algol
RS Ari	9·82	10·90	10·20	8·803146	F9+G5	Algol
SX Aur	8·21	8·97	8·67	1·210077	B4+B4	β Lyr
S Cnc	8·00	10·22	8·05	9·484524	A0+G5	Algol
YY CMi	8·50	9·11	8·90	1·094065	F5	β Lyr
ST Car	9·08	10·40	9·33	0·901649	A0+F6	Algol
V Crt	9·50	10·20	9·90	0·702034	A6	β Lyr
RZ Eri	7·78	9·03	8·00	39·281900	dF5+G8	Algol
RT Lac	8·80	9·60	9·50	5·073977	G9+K1	β Lyr
β Lyr	3·40	4·32	3·82	12·908006	B8p	β Lyr
Z Ori	9·60	10·50	9·70	5·203250	B4	Algol
δ Ori	2·40*	2·55*	2·52*	5·732500	B0	Algol
ST Per	9·66	13·15	9·76	2·648355	A3+K	Algol
β Per	2·20	3·47	2·26	2·867310	B8	Algol
V Pup	4·53	5·14	3·82	1·454487	B1+B3	Algol
U Sge	6·36	9·04	6·46	3·380618	B9+G2	Algol
SV Tau	9·71	10·80	9·86	2·166903	B9+A0	Algol
RW UMa	9·94	10·94	10·07	7·328269	F9+G9	Algol
W UMi	8·61	9·73	8·78	1·701160	A3	Algol
α Vir	1·20*	1·30*	1·28*	4·014160	B3n	Algol

* Photoelectric magnitude

Knowing the masses and also the dimensions, the densities may be easily found. In the case of U Cephei, for example, we can now say that the brighter star is of spectral type B8 with a surface temperature of around 14,000°C. The mass and diameter are 4·7 and 5·8 times that of the Sun. The fainter companion is a G-type subgiant with a surface temperature in the region of 6,000°C, and a mass of only 1·9 times that of the Sun. Its diameter, however, is 9·2 times as great. Moreover, the distance between the centres of the two stars is only about 10,000,000 kilometres, or some 4,500,000 kilometres from the surface of one star to that of the other. In fact, we find that this second figure is no greater than the diameter of the larger star itself!

THE PULSATING VARIABLES

We now come to the second large class of variable stars, those whose light changes are an intrinsic property of the star itself and not the result of a purely fortuitous set of external circumstances. For this reason they, and the eruptive variables we shall be discussing later, are known as the intrinsic variables.

There are several different types included within this group. Some have extremely regular, stable periods while at the other end of the scale we find stars which seem to have no recognizable period at all. The reason for these differences in behaviour is found to lie in the stars themselves, in the physical mechanism responsible for the light variations. Here we shall examine each of the main classes in turn.

The RR Lyrae and Cepheid Variables. It is convenient here to consider these two classes of variable together although as we shall see later there are certain differences between them. One of the brightest stars of this group, and the first to be discovered by Goodricke in 1784, is δ Cephei. This star varies between 3·78 and 4·63 magnitude in a period of 5·366 days and quite clearly the light curve (Fig. 15) is unlike that of the eclipsing variables.

Throughout its light cycle the spectrum of this star varies from F5 to G2 indicative of a change in surface temperature. At present some 500 Cepheids are known, all having somewhat similar light curves although in certain cases there are more or less well-defined humps on either the ascending or descending branches of the light curve. Indeed, this irregularity sometimes coincides with the maximum which then appears abnormally pointed. Gaposchkin has shown from a detailed study of these stars that this asymmetry

becomes more pronounced as we consider stars of longer and longer period and at the same time there is also a tendency for these humps to be displaced steadily along the curve.

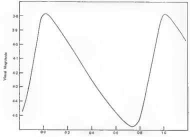


Fig. 15. *Light curve of δ Cephei*

In general, this group of variables is divided into three sub-classes:

1. The RR Lyrae variables, also known as cluster variables since they are found in large numbers in the globular clusters. These stars all have periods of less than one day.

2. The classical Cepheids with periods between 1·5 and 28 days, and

3. The long period Cepheids with periods in excess of 28 days.

At first it was thought that all three groups of variables formed one single family and any differences there were among them were only of degree and not of kind. More recent work has invalidated this idea and we now know that although the physical mechanism operating within them to produce the characteristic light variations is probably the same, the RR Lyrae stars differ in many important respects from the others. As we shall now see a great

deal of confusion arose before these differences were recognized by astronomers.

In 1913, Miss Leavitt, working at the Harvard College Observatory, plotted the periods of the numerous Cepheids found in the Magellanic Clouds against their apparent brightness and discovered a relationship between these two parameters, namely that the longer the period, the brighter was the mean magnitude. Had this been done for the Cepheids in our own galaxy this would have meant very little since the apparent brightness is greatly affected by distance. The overall dimensions of the Magellanic Clouds, however, are small compared with their distance from us (approximately 180,000 light years) and consequently we may regard all of the stars within the Clouds as being at essentially the same distance. Hence any discrepancy between the apparent and the absolute magnitudes of these Cepheids will be a constant factor.

In other words if we take the Cepheids in any particular group of stars, for example the Magellanic Clouds or any of the external galaxies, and plot the periods against the apparent magnitudes, we obtain a smooth curve for each group and all of these curves will be superimposable simply by moving them up or down the magnitude axis (Fig. 16).

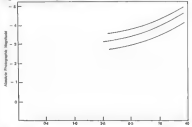


Fig. 16. *Period-luminosity curves for Cepheids in different stellar associations*

Once this important period-luminosity relationship was established, astronomers directed their attention to the RR Lyrae stars as these would obviously prove useful for finding the distances to the numerous globular clusters which form a kind of halo around the galaxy. Knowing the absolute magnitude of a star, its distance may readily be calculated from the following equation.

$$M - m = 5 - 5 \log D \quad (3)$$

where M is the absolute magnitude, m the apparent magnitude, and D is the distance in parsecs.

Now although we have this period-luminosity relationship, there still remains one problem to be overcome before we can use it to determine distances. To locate the zero point on the graph we must know the absolute magnitude of at least one Cepheid otherwise we can measure only relative distances. This proves to be a very difficult problem since the nearest of the galactic Cepheids is more than 300 light years away.

The position with the RR Lyrae stars is somewhat different, however, in that they possess large proper motions and it is possible to determine the mean distances of certain groups of these variables by statistical methods which utilize the uniform motion of the Sun through space. All of the results obtained for the RR Lyrae variables are in very good agreement and the latest measurements show that they have about the same absolute magnitude of +0·8.

Using this as a starting point, astronomers calculated the distances of the Cepheids in the Magellanic Clouds and also in some of the nearer spiral galaxies, particularly Messier 31 in Andromeda. These determinations indicated a distance of about 980,000 light years for M31 corresponding to an apparent magnitude of 22·4 for the RR Lyrae stars within this galaxy. Unfortunately for the theory, once the 200-inch Hale telescope at Mount Palomar came into operation, there was no sign of any RR Lyrae variables on the photographic plates although the limiting magnitude of this instrument is 24. At this stage there were two possible alternatives. Either M31 is totally unlike our own galaxy in that it contains virtually none of these variables (an alternative which, even at that time, was unthinkable to most astronomers) or the galaxy is much further away than the distance suggested by the Cepheid scale.

To test this second possibility, Baade made use of the long-period variables (stars like Mira to be discussed later) which are

not only fairly readily recognized by their typical light variations and periods but which are known from repeated and concordant measurements to have an average absolute magnitude of −1·5. Their spectra, too, contain emission lines of hydrogen and the characteristic absorption bands of certain molecules such as titanium and zirconium oxides making them easily identifiable. From a study of several long-period variables in M31, Baade was able to show that the distance to the galaxy is 2,200,000 light years, more than double that found earlier.

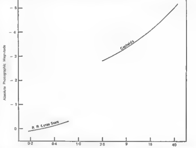


Fig. 17. *Period-luminosity curves of RR Lyrae stars and classical Cepheids*

The answer to this curious anomaly came when it was recognized that the RR Lyrae stars and the Cepheids belong to two different types of stars and that we cannot apply the same relationship found for one to the other. The former belong to Baade's Population II stars which are the oldest stars formed out of the primal gas of the galaxies and found in the globular clusters and the galactic nuclei. The Cepheids, on the other hand, belong to the Population I stars, those like the Sun which are, in general, appreciably

younger and are found in the spiral arms of the galaxies. This difference is well brought out in Fig. 17 which shows the two different period-luminosity curves for the two classes of variable.

So far we have said very little about the basic cause of the light variations of these variables. The idea advanced by Shapley and Eddington that they are pulsating stars is now generally accepted but as to why these stars pulsate in this manner is a problem still not fully understood. When we analyse the light and radial velocity curves we find that the star is brightest about a quarter of a period before it reaches its greatest diameter. This is simply because as it expands, the surface temperature falls and this more than compensates for the increase in surface area (Fig. 18). Whether the entire star partakes of this rhythmic expansion and contraction or merely the outermost layers is still a debatable point although the latter seems more probable. Certainly the change in diameter

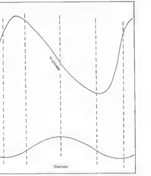


Fig. 18. *Variation in diameter of a Cepheid variable with the changes in the light curve*

which is necessary to explain the observed variations in brightness cannot be much more than 10 per cent of the total diameter.

Before leaving this particular type of variable it is perhaps worth mentioning a very small group of stars whose prototype is the second magnitude star β Canis Majoris. The amplitudes of these stars are much smaller than those of the Cepheids, very seldom exceeding 0 1 magnitude, and sensitive photoelectric equipment is required to follow their light changes. Although only a small number are known at the present time, this is due to the difficulty in detecting the minute changes in luminosity and not to a real rarity of these stars for it has been estimated that several hundred exist within the galaxy.

Like the RR Lyrae stars, their periods are very short – generally between 3 and 9 hours – but their most peculiar characteristic is that after varying quite regularly for several years, their light variations diminish and finally die out altogether. After remaining

Table 2

RR LYRAE AND CEPHEID VARIABLES

Star	*Magnitude* *Max*	*Min*	*Period* *(days)*	*Spectrum*	*Type*
SW And	9·3	10·3	0·442278	A3 – F8	RR Lyr
TT Aql	7·0	7·7	13·754750	F8 – K0	Cepheid
SY Aur	8·8	9·5	10·144026	G0 – G2	Cepheid
U Car	6 5	8·2	38·749377	F9 – K3	Cepheid
XY Cas	9·7	10·4	4·501760	F8 – K0	Cepheid
RZ Cep	9·6	10·2	0·308679	A0 – A3	RR Lyr
δ Cep	3·78	4·63	5·366306	F5 – G2	Cepheid
QT CrA	11·4*	12·5*	79·145	A – K	Cepheid
SU Cyg	6·4	7·1	3·845507	F0 – G1	Cepheid
SU Dra	9·7	10·6	0·660419	A2 – A5	RR Lyr
RX Eri	9·0	9·9	0·587245	A3 – F0	RR Lyr
ν Eri	3·38†	3·52†	0·173507	B2s	CMa
VX Her	9·9	11·1	0·455372	A3 – F0	RR Lyr
Z Lac	8·7	10·4	10·885824	F6 – G6	Cepheid
UZ Leo	9·2	9·7	0·309205	A3 – F0	RR Lyr
EH Lib	9·5*	10·1*	0·088414	A5 – F0	RR Lyr
Y Oph	6·9*	7·8*	17·118140	F9 – G5	Cepheid
DY Peg	10·1	10·7	0·072926	A3 – A9	RR Lyr
U Sgr	6·9*	8·0*	6·744918	F7 – G5	Cepheid
σ Sco	2·83†	2·91†	0·246841	B1	CMa

* Photographic magnitude † Photoelectric magnitude

constant in brightness for some time, the fluctuations begin once more, small at first but gradually building up to their original amplitude. The radial velocity curves of these stars often show quite pronounced irregularities and it is now generally believed that these, and the puzzling light variations, are due to small, but fairly stable pulsations in the outer atmospheric levels of these stars. One star in which this peculiar behaviour is very noticeable is γ Boötis.

The spectra of these stars show that they belong mainly to Type B, their surface temperatures lying in the range 8,000° to 16,000°C. They are therefore somewhat hotter than either the RR Lyrae or Cepheid variables which, from Table 2, will be seen to be predominantly of spectral types A or F. Like the other pulsating stars just discussed, the lines in their spectra are sharp and narrow, indicative of a low velocity of axial rotation.

The Long-Period Variables. The type star of this large and important class is ο Ceti (Mira) which, as we have already seen, was found to be variable as long ago as 1596 although the periodic nature of the light variations was not discovered until 1638 by Holwarda. As their name implies, these variables have longer periods than the Cepheids we have just discussed, ranging from almost 100 to more than 700 days.

All of the long-period variables are red stars indicative of low surface temperaures. Their spectroscopic types are almost exclusively M, N, and S. Type M spectra are dominated by fluted bands produced by titanium oxide. The surface temperature ranges from 2,000°C to 3,000°C, and at the lower end of the scale it is certainly not high enough to dissociate this very stable compound into its component atoms. Around the time of maximum brightness, the hydrogen lines appear in emission. The N-type stars have similar spectra but in this case the fluted absorption bands are due to carbon compounds and although there are some difficulties in assessing their surface temperatures accurately these are probably not unlike those of the M-type stars. Finally, the S-type spectra are almost identical to those of Type M, the absorption bands being due in this case to zirconium oxide.

An examination of Fig. 19 shows that the light changes of these stars are by no means as regular as those of the Cepheids. It is quite impossible to predict the date, shape or amplitude of any one maximum from those which have preceded it and for this reason alone, continuous observation of these variables is of the utmost

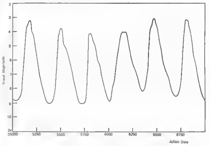


Fig. 19. *Light curve of Mira (ο Ceti)*

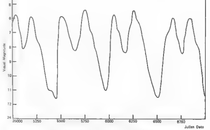


Fig. 20. *Light curve of R Centauri*

importance. The minima, too, vary somewhat but to a lesser extent than the maxima. Mira, for example, may attain anything between second and fifth magnitude at its brightest and on one occasion, in 1779, it reached first magnitude, rivalling Aldebaran in brightness.

Very often, the light curve is distorted by a pronounced hump which, as in the case of the Cepheids, may be on either the ascending or descending branch of the light curve. The position of this hump varies markedly from one cycle to the next and may even be absent altogether on occasion. Some of these stars are known in which this irregularity is so marked that it produces what appears to be a secondary minimum. R Centauri (Fig. 20) is a very good example of this.

Since the amplitudes of these stars are usually large, sometimes as great as 11 magnitudes (e.g. χ Cygni), and their overall light changes relatively slow, they make ideal objects for amateur observation, and up to the present time more than a million and a half observations of long-period variables have been made by the American Association of Variable Star Observers and the Variable Star Section of the British Astronomical Association. From the results obtained over more than half a century, the main forms taken by their light curves are quite well known.

The temperature changes and also the variations in the effective diameters of these stars, which go hand in hand with the light changes, are relatively small, particularly when we consider that at maximum brightness the star may be as much as 100,000 times brighter than when at minimum. This large change in visual brightness, however, is somewhat misleading. If we use an instrument known as a bolometer which effectively measures the total radiation emitted by these stars (including the infra-red and ultra-violet which are absorbed by our own atmosphere) we find that the bolometric magnitude is only about twice as great at maximum as at minimum. To understand why this is so we must look a little more closely at the visible spectrum. As the star fades towards minimum, the intensity of the absorption bands increases, blotting out most of the spectrum and effectively reducing the amount of visible light reaching us. The ultra-violet and infra-red radiation, however, is only marginally reduced.

From the radial curves of the long-period variables there seems little doubt that, like the Cepheids, these are also pulsating stars. When the star expands there is an associated lowering of the surface temperature which results in atoms of titanium, carbon, or zirconium combining with either oxygen or hydrogen to form stable compounds.

When we compare the pulsations of these stars with those of the RR Lyrae and Cepheid variables we find certain differences.

Table 3

LONG-PERIOD VARIABLES

Star	*Magnitude* Max	*Magnitude* Min	*Mean period (days)*	*Spectrum*
R And	5·0	15·3	408·87	Se
W And	6·5	14·2	397·05	M8e
R Aql	5·1	12·0	300·00	M7e
S Cas	6·2	15·3	611·83	Se
T Cen	5·2	10·0	90·65	M0e
T Cep	5·2	11·2	388·35	M7e
T Col	6·6	12·6	225·27	M4e
V CrB	6·8	12·4	357·64	Ne
χ Cyg	2·3	14·3	406·66	Mpe
S Her	5·9	13·8	307·18	M6e
R Leo	4·4	11·6	313·13	M8e
W Lyr	7·2	13·1	195·98	M4e
R Ori	8·5	13·4	378·52	Se
R Sgr	6·6	13·3	268·83	M5e
RR Sco	5·0	12·2	279·45	M6e
R Ser	5·6	14·0	357·10	M7e
R Tau	7·4	15·1	324·02	M5e
R Tri	5·4	12·0	265·91	M4e
R UMa	6·1	13·6	301·21	M4e
S Vir	6·0	13·0	377·11	M7e

The long-period variables are giant or supergiant stars with very low densities, and pulsations within such stars will be less stable than those within the Cepheids. In addition, there is now some evidence that shock waves develop within the grossly distended atmospheres and travel outward towards the photosphere, often attaining supersonic velocities. As the shock wave dissipates, it causes the outer gases to cool and this cooling also produces molecules.

Semi-Regular and Irregular Variables. As we have just seen, the light variations of the long-period variables do not exhibit the almost perfect regularity such as is shown by many of the eclipsing and Cepheid variables. This deviation from a regular light variation is even more pronounced when we come to consider the semi-regular stars.

In 1796, Sir William Herschel studied the third magnitude star α Herculis which varies between 3·0 and 4·0 magnitude in a manner which seems to be quite irregular. His son, John Herschel, who continued this work, drew attention to several similar stars which differed from the long-period variables in that there was no obvious pattern to their light changes. Not until a large amount of observational data became available was it possible to show that although there undoubtedly exist some stars for which no trace of periodicity whatever can be found – the true irregular variables – in several, a kind of pseudo-period is present which may, however, be only of a transitory nature.

Like the long-period variables, the semi-regular variables are all red stars. Their amplitudes are almost invariably smaller than those of the long-period variables, seldom exceeding two magnitudes. Very often, too, we find that superimposed upon the primary period there is a much longer secondary wave. Indeed, stars are known in which there are three or four periods of different length

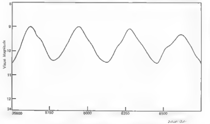


Fig. 21. *Light curve of R Ursae Minoris*

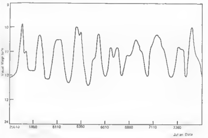


Fig. 22. *Light curve of U Boötis*

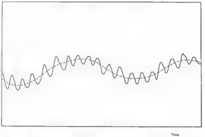


Fig. 23. *Light curve of a semi-regular variable showing the presence of a secondary period*

all superimposed upon each other adding to the complexity of the light variation. Fortunately a number of these stars are quite bright objects and the whole of their light cycles may be followed with no other instrumental aid than a pair of binoculars.

Owing to their complex light curves it is not an easy matter to classify this very heterogeneous group. However, four somewhat arbitrary sub-classes have been recognized by astronomers, these being as follows:

Type SRa: these are all giant or supergiant stars of spectral classes M, N, or S and in general their light curves are very similar to those of the long-period variables. Quite often, the only way we have of differentiating them is their smaller amplitudes. S Aquilae and R Ursae Minoris are examples of the SRa variables (Fig. 21).

Type SRb: it is often difficult to distinguish these variables either from the long-period variables or the SRa type since their light curves are very similar. At times, however, the SRb stars undergo much slower and more irregular fluctuations in brightness and there may even be protracted periods when the light remains essentially constant. One of the best known of these stars is U Boötis (Fig. 22). One particular feature of this star which allies it very closely with the long-period variables is that, unlike the majority of the semi-regular variables, its spectrum shows bright emission lines throughout most of its light cycle.

Type SRc: this is a fairly large group of stars, many of them being naked-eye objects such as Betelgeuse (α Orionis) and α Herculis. They have quite small amplitudes, normally of the order of a single magnitude, and this adds to the difficulties of determining their light variations accurately. One further difficulty with these very bright stars is the lack of nearby stars of comparable brightness against which to measure their fluctuations. The presence of long, secondary waves superimposed upon the somewhat shorter, more irregular light variations is quite a common feature of these variables (Fig. 23).

Type SRd: the stars belonging to this type have earlier spectra than those already discussed, usually of types F, G, and K. All are highly luminous objects and are either giants or supergiants. Here we may also, for convenience, include the RV Tauri variables although most astronomers now regard the two classes as being quite distinct. In general, the light curves are typified by alternate deep and shallow minima (Fig. 24) and until a few years ago a great deal of confusion existed about these two groups.

Spectroscopic examination has now revealed that whereas the SRd variables show quite strong and persistent emission lines of hydrogen in their spectra, this feature is virtually absent in the RV Tauri stars. Their absorption spectra, too, show certain differences. Absorption lines of hydrogen are quite strong in the RV Tauri stars but either very weak or absent altogether in the SRd variables. During the deep minima of the RV Tauri variables, strong absorption bands of titanium oxide appear and during this phase the spectra are strongly reminiscent of the long-period variables. One further fundamental difference is that the SRd stars belong to Baade's Population II stars. The members of the RV Tauri class, on the other hand, are more closely allied to the Population I stars.

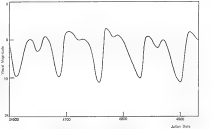


Fig. 24. *Light curve of R Sagittae*

Perhaps it is inevitable that the semi-regular stars should be compared with the long-period variables. In particular, the SRa and SRb variables have many points in common with the Mira-type stars. Let us now examine the various points of difference between them. From a detailed study of the light curves of all these variables, we find that whereas the long-period variables show a marked family resemblance among the individual members, this is not the case for the semi-regular variables. Because of the wide differences in their behaviour it is sometimes

better, and more convenient, to consider each particular star on its merits. The nature of the light changes, especially those where one or more subsidiary waves are superimposed upon the basic cycle, suggests that within the atmospheric levels of these stars more than one mode of oscillation is present. These pulsations may individually be quite regular but varying independently of the others and the complex behaviour is due to interference of one oscillation with another.

The spectra of the semi-regular variables posed a special problem to the early investigators. By far the greater proportion of these stars are of spectral types M and N but a comparison of the data given in Tables 3 and 4 shows that whereas the spectra of the long-period variables are characterized by bright emission lines, this feature seems to be conspicuously absent in those of the semi-regular stars and, incidentally, in those of the irregulars.

Table 4
SEMI-REGULAR VARIABLES

Star	*Magnitude*		*Period*		*Spectrum*	*Type*
	Max	*Min*	*Primary (days)*	*Secondary (days)*		
AD Aql	10·9	12·1	65·4	—	F – M	RV Tau
U Boo	8·4	13·3	185·8	—	M4e	SRb
VZ Cam	4·7	5·2	24·0	—	M4	SRb?
SV Cae	6·8	10·1	278·0	—	M5	SRa
SX Cen	9·9*	12·4*	32·8	—	F5	RV Tau
SS Cep	6·7	7·8	99·0	1435	M5	SRb?
AM CrA	9·8*	11·1*	187·0	—	M3	SRa
W Cyg	5·0	7·6	130·6	3100?	M4e	SRb
R Dor	7·1*	8·1*	338·0	—	M7	SRb
S Dra	8·2	9·4	342·0	1310	M6	SRb
α Her	3·0	4·0	100·0	2170	M5	SRc
S Lep	6·0	7·4	95·0	835	M6	SRb
R Lyr	4·0	5·0	50·0	—	M5	SRc?
α Ori	0·4	1·3	2070·0	—	cM2	SRc
S Per	7·2	12·2	810·0	916	cM3e	SRa
R Sge	9·0*	11·5*	70·8	—	G0 – G7	RV Tau
R Sct	5·0	8·4	144·0	—	G0 – M5	RV Tau
RV Tau	9·3	12·7	78·6	1227	KIv	RV Tau
VW UMa	7·2	7·8	125·0	—	Ma	SRb?
R UMi	8·7	10·7	324·8	—	M7e	SRa

* Photographic magnitude

Originally, it was believed that this represented a fundamental difference between the two classes of star. This view is no longer held by variable star observers since we now know that it was based upon insufficient spectroscopic evidence. In the long-period variables the bright emission lines begin to appear about a quarter of the period before maximum and fade as the brightness diminishes towards minimum. They are not visible throughout the whole of the light cycle.

As more and more spectroscopic data became available for the semi-regular stars it was found that here too, emission lines are visible in the spectra; but owing to the complex nature of the light curves they are observable for shorter periods and their presence had been missed by the early investigators.

This failure to detect them is even more understandable in the case of the irregular variables since it is much more difficult to predict when the maxima should occur.

The Irregular Variables. We now come to those stars in which all trace of periodicity has vanished. It is particularly unfortunate that these stars did not receive the same detailed study over the past century as the long-period variables for although many hundreds are known, we have light curves for only a small number. Quite possibly, as more information becomes available, some may be found to exhibit a degree of regularity which will necessitate placing them among the semi-regular stars.

The amplitudes of the irregular variables are again quite small, certainly nothing like those of the long-period variables. In addition, many vary in brightness only at infrequent intervals and then only by small amounts. From the very beginning it was perhaps only to be expected that this class of star should include many dissimilar variables, all grouped together under the heading of 'irregular' more for convenience than anything else.

We find, for example, stars like γ Cassiopeiae which have Be-type spectra and are therefore very hot, bright objects. The irregular nature of the light fluctuations of γ Cassiopeiae is shown in Fig. 25.

Since this group contains many bright representatives, we now know a great deal about their spectra which give us some idea of the possible cause of the changes in luminosity. It thus appears that these stars are rotating very rapidly on their axes so that mass is being ejected to form either a disc around the star or a grossly distended atmosphere which extends in the form of a shell of gas

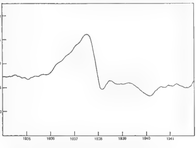


Fig. 25. *Light curve of γ Cassiopeiae*

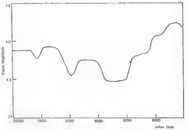


Fig. 26. *Light curve of μ Cephei*

to a great distance from the star. The presence of violent, but fairly localized, disturbances within this gaseous shell has been suggested to explain the changes which take place in their spectra.

At the other end of the temperature scale, we have variables like μ Cephei which is a red giant of spectral type M2e. The light curve shown in Fig. 26 illustrates the peculiar long plateaux which are a feature of this star. Although we are still far from a proper understanding of the cause of these odd light variations, one suggestion which has been advanced is worthy of consideration.

Table 5

IRREGULAR VARIABLES

Star	*Magnitude* *Max*	*Min*	*Spectrum*
V Aql	6·7	8·2	N
V Ari	7·7*	8·3*	R4
UZ Aur	8·2	9·0	M4
S Cae	9·7*	10·5*	K
W CMa	8·3*	10·0*	N
γ Cas	1·6	3·0	B0e
μ Cep	3·6	5·1	cM3e
SW CrB	7·6	8·3	M1
R Crt	9·8*	10·4*	M4
TZ Cyg	9·6	11·2	M7
U Del	5·6	7·5	M5
TV Gem	6·6	8·0	cM2
BO Mus	6·0	6·7	Mb
BL Ori	6·3	6·9	N
T Per	8·3	9·3	cM1
Y Pic	9·1*	9·5*	M2
Z Psc	7·0	7·9	N
UX Sgr	7·6	8·4	Mb
ST Sco	7·8	9·7	R5
TT UMa	8·9	9·5	M6

* Photographic magnitude

Let us suppose that there are regions upon the surface of this giant star where the effective temperature is either higher or lower than over the remainder of the surface. Since the observed light changes are quite small it is not necessary for us to postulate the presence of a steep temperature gradient within these areas. Now

if the normal state of μ Cephei is represented by an optimum magnitude of about 4·2, then depending upon whether the temperature of these abnormal localized regions is above or below the normal surface temperature we will get long, flat plateaux which lie either above or below this optimum magnitude.

Quite clearly, if this picture is anywhere near the truth, the period of axial rotation of this star must be fairly long – at least several hundred days – in order to explain the rather lengthy periods of almost constant brightness.

The Nebular Variables. The irregular variables we have just discussed all have one thing in common. The light variations are brought about more by internal influence than any external agency. There are, however, many stars which can only be classed as irregular but which owe their changes in brightness more to their environment than to any nuclear or physical changes in their interiors. Such stars are generally known as nebular variables although it is possible to distinguish three sub-classes. All are associated in some way with dark or bright nebulosities.

Large numbers of nebular variables are found in the Orion Nebula and in the neighbouring constellations of Auriga and Taurus. Similar regions which are literally teeming with these stars have been discovered in the southern hemisphere in Carina, Corona

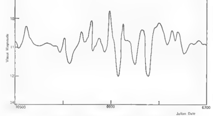


Fig. 27. *Light curve of RW Aurigae*

Australis, and Monoceros. Since there is no regularity at all to be found in their very complex variations, the task of classifying them might seem an insurmountable one. Fortunately, their spectra provide the information we need.

1. *RW Aurigae variables*: in general, these stars have fairly large amplitudes (usually two or three magnitudes) and light curves characterized by rapid and completely irregular fluctuations (Fig. 27). Quite a number of RW Aurigae variables are found in the Orion Nebula in association with the T Orionis variables mentioned below and in those cases where only the light curves are available for study it is often extremely difficult to differentiate between the two classes. Where it is possible to obtain the spectrum, however, we find that the RW Aurigae stars are almost exclusively G-type dwarfs whereas the latter have much earlier spectra, being mainly of types B or A.

2. *T Orionis variables*: these stars have light curves (Fig. 28) similar to those of the preceding class, marked by irregular fadings normally of two or three magnitudes. Unlike the RW Aurigae stars, they have quite high surface temperatures between 11,000° and 25,000°C, those of the former being much like that of the Sun. They also seem to be giant stars rather than dwarfs.

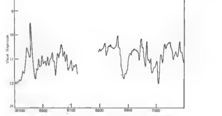


Fig. 28. *Light curve of MR Orionis*

From the evidence we have at the moment it appears quite probable that these are young stars condensing out of the vast gas clouds in which they are embedded. This is substantiated to a certain extent by their marked tendency to aggregate in well-defined regions and the fact that they are always associated with bright nebulosities.

3. *T Tauri variables*: the amplitudes of these stars are usually smaller than those of either of the preceding classes although some, like T Tauri itself, vary by more than three magnitudes. The spectra are predominantly later than either the RW Aurigae or T Orionis variables indicating that they are red dwarfs. One further point of difference is that the nebulosities with which they are intimately associated are usually quite small and often dark rather than bright.

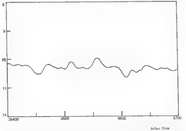


Fig. 29. *Light curve of T Tauri*

Because of this we sometimes find that the brightness of the surrounding nebula is also variable although in most cases the fluctuations in the light of these tiny nebulosities are greater than those of the stars themselves. This would suggest that the gas clouds vary in brightness independently of the stars themselves. We must, however, be a little cautious in interpreting this observation since it is quite possible that small changes in the visual brightness

of the variables may be accompanied by much larger variations in both their infra-red and ultra-violet radiation, both of which can have a profound effect upon the brightness of the surrounding gas cloud.

The light curves of the T Tauri stars (Fig. 29) often tend to show evidence of sinusoidal waves and like the T Orionis stars they are relatively young objects, their spectra showing several remarkable features. For example, they indicate a very high abundance of lithium in the atmospheres of these stars, about 100 times greater than that found in the Sun. The dark absorption lines, too, are unusually broad, indicative of a high velocity of rotation. Indeed, no other stars with similar spectra lying close to the main sequence are known with such high rotational velocities. When we extend the spectroscopic measurements into the infra-red region, the results are compatible with a model in which a contracting central star is surrounded by a disc of dust. The energy which is being released by the star due to its contraction appears to be transferred to this rotating disc and some astronomers are of the opinion that here we have planetary systems in the making.

Table 6

NEBULAR VARIABLES

Star	*Magnitude* *Max*	*Min*	*Spectrum*	*Type*
RW Aur	9·0	12·0	dG5	RW Aur
T Cha	10·0*	13·2*	dG5	RW Aur
RU Lup	9·3*	13·2*	dG5e	RW Aur
R Mon	10·0	14·3	G5	RW Aur
CO Ori	10·0	13·0	dK0	RW Aur
RR Tau	10·2	14·2	G1	RW Aur
TT CrA	8·7	12·4	F0	T Ori
T Ori	9·5	12·1	A0	T Ori
RY Ori	10·5*	14·0*	A0	T Ori
SW Ori	12·9*	16·0*	A0	T Ori
TV Ori	13·4*	15·6*	F0	T Ori
UX Ori	8·9*	10·6*	A2e	T Ori
SU Aur	9·0	9·6	dG2	T Tau
AN Ori	10·7	11·7	dK1e	T Tau
T Tau	9·5	13·0	dG5e	T Tau
RY Tau	8·6	11·0	dG0e	T Tau
DD Tau	14·1*	15·5*	dK6e	T Tau
DE Tau	13·9*	14·6*	dM1e	T Tau

* Photographic magnitude

Most of the nebular variables are, unfortunately, quite faint objects even at maximum brightness and fairly large telescopes are necessary to follow them throughout their light cycles. Inevitably, therefore, there is quite a lot of overlapping among the three classes and the fact that there is also this close association of all three types within large regions of nebulosity further complicates matters.

R Coronae Borealis Variables. This is a small and peculiar class of variable star typified by R Coronae Borealis. Normally, this star is just visible to the naked eye but at irregular intervals it fades, often quite rapidly, to anything between seventh and fourteenth magnitude. The eventual climb back to maximum is more protracted and often accompanied by marked fluctuations (Fig. 30).

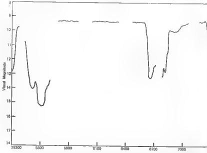


Fig. 30. *Light curve of RY Sagittarii*

Quite clearly, from the light curve, it is impossible to reconcile these unpredictable light variations with any kind of pulsatory mechanism as is present in the long-period variables which have

similar amplitudes. In order to understand the reasons for the peculiar behaviour we must examine the spectra of these stars. An examination of Table 7 reveals the curious fact that a high proportion of them have spectra of the rare type-R although a few are known, including the prototype itself, which are of the earlier spectral class G. We also find one variable – V348 Sagittarii – which has an O9 spectrum. If this star is indeed an R Coronae Borealis variable, and the light curve shows a marked similarity to those of the other members, then its surface temperature of around 35,000°C is the highest of the entire group.

Table 7
R CORONAE BOREALIS VARIABLES

Star	*Magnitude* *Max*	*Min*	*Spectrum*
S Aps	9·6	15·2	R3
XX Cam	8·7*	10·3*	—
UV Cas	11·8*	16·5*	R0?
UW Cen	9·6*	(16·0*	K
DY Cen	12·0*	(16·4*	—
V504 Cen	12·0*	(18·0*	R0?
AE Cir	12·2*	16·4*	—
WX CrA	11·0*	(16·5*	R5
R CrB	5·8	14·4	cG0ep
Y Mus	10·5*	12·1*	R0?
RT Nor	11·5*	14·9*	R2?
SV Sge	11·6*	13·9*	R2
RY Sgr	6·0	14·0	cG0ep
GU Sgr	11·0*	13·8*	—
V348 Sgr	11·0*	(16·5*	09
V618 Sgr	11·0*	(16·5*	—
SU Tau	9·5	16·0	cG0ep
RS Tel	9·3*	14·6*	R8
VZ Tel†	11·6	14·1	—
RZ Vul†	13·0*	(16·0*	—

* Photographic magnitude † Probable members of this class

The main feature of the spectra of these variables is the abundance of carbon and its compounds and the abnormally low proportion of hydrogen. The majority have surface temperatures of about 7,000°C and this is the region in which carbon will condense from the gaseous to the solid state. Now we know that particles of

carbon, even of microscopic size, are very good light absorbers and this is the most likely cause of the typical light fluctuations. Although we do not know the precise mechanism whereby these highly absorbing layers are produced there would seem to be two possibilities.

1. Due to slight variations in the surface temperature, the tiny carbon particles are formed within the outer levels of the atmosphere of the star, being gradually transformed back into the gaseous state whenever the temperature rises again.

2. At irregular intervals, the star ejects a shell of gas which cools off at some distance from it. As this shell contracts, the density rises and carbon particles are deposited, absorbing an appreciable proportion of the light of the star. As the shell dissipates, the brightness returns to normal.

A third possiblity is that these stars may be embedded in dark nebulosity rather like the T Tauri variables described earlier. Certainly several patches of obscuring matter exist within the galaxy. There is, however, one grave objection to this idea. Spectroscopic analysis of these dark clouds has revealed that none of them contain the high proportion of carbon necessary to explain the observed spectroscopic changes in the R Coronae Borealis variables. This theory has now been largely abandoned.

Although the light changes of these stars have a great deal in common it must not be imagined that there are no differences among them. The frequency of the deep minima varies appreciably from one star to another. The longest period during which R Coronae Borealis has remained at maximum is nine years (from 1925 to 1934) whereas other variables, for example MV Sagittarii, have faded only once in half a century or more. For this reason alone, these stars should be observed on every possible occasion since there is no way of telling when they will commence a spectacular fading.

THE ERUPTIVE VARIABLES

These are stars which are normally very faint but which abruptly increase in brilliance by several magnitudes often in the course of a single day. Four main classes may be distinguished, namely the dwarf novae which comprise the U Geminorum and Z Camelopardalis variables, the novae, the recurrent novae, and the supernovae.

The term 'nova', meaning a new star, was given to these objects in pre-telescopic times when their true nature was not recognized.

This is quite understandable since it did seem to the astronomers of those days that such stars appeared spontaneously and then vanished once more without trace. When the large telescopes came into operation and particularly when long-exposure photographs became available for examination, it was found that in many cases an extremely faint star existed in the position of the nova before the outburst. Then too, it was possible to follow a typical nova throughout the whole of its decline to minimum when the star returned to something like its initial state.

Obviously, therefore, the novae are simply stars which undergo a truly catastrophic explosive outburst of some kind. It is this outburst which is the temporary phenomenon and not the star itself. As we shall see, several novae often rival the brightest stars when at maximum and are then readily visible to the naked eye. Nova Persei (1901), for example, attained magnitude 0·2 at its brightest, having previously been a star of fourteenth magnitude, while Nova Aquilae (1918) was even brighter, reaching −1·4 magnitude and equalling Sirius in brilliancy. Such behaviour is even more dramatic in the case of the galactic supernovae although these are of much rarer occurrence.

The Dwarf Novae. Before discussing the novae and supernovae, we must first consider a small and remarkable group of variables which, at least as far as their light curves are concerned, closely resemble the novae. The first of these stars – U Geminorum – was discovered by Hind in December 1855 when it was of ninth magnitude. Two weeks later it was no longer visible in Hind's telescope and it was thought to have been merely a faint nova, many of which had been discovered prior to that date. Some three months later, it was observed again at maximum by Pogson and it soon became evident that a completely new type of variable had been discovered. Since that time, two hundred or so of these stars have been found, all being fairly readily identified by their characteristic light curves. By far the larger number are similar to U Geminorum with light curves typified by rapid increases in brightness by between two and six magnitudes followed by a slower decline to minimum. The light curve of a typical U Geminorum variable is shown in Fig. 31.

A small subgroup containing a score or so members is now recognized by astronomers. The prototype is Z Camelopardalis which varies between 10·2 and 13·4 magnitude in a mean period of 20 days. In their general behaviour they are very like the U

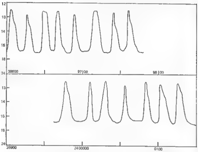


Fig. 31. *Light curve of FQ Scorpii*

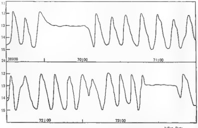


Fig. 32. *Light curve of CN Orionis*

Geminorum stars, subject to similar nova-like outbursts although their mean periods are normally shorter, they spend less time at minimum and they have smaller amplitudes. The major difference, and that which justifies their inclusion in a separate subgroup, is the periods of 'standstill'. Following certain maxima, the brightness does not fade to a normal minimum but remains virtually constant at some intermediate magnitude.

From Fig. 32 it will be seen that a 'standstill' may last anything from a few days to several months. Usually it ends with a fall to minimum when the more normal behaviour will begin again but on a few occasions a standstill has terminated in a rise to maximum.

For many years it was considered that the outbursts of the dwarf novae were essentially the same as those of the ordinary novae, namely an explosive ejection of gas due to some unstable condition within the outer levels of the star. When we examine the spectra of these stars, however, we find no evidence at all of high-temperature gas approaching us during a typical outburst. There is one feature which these variables do have in common with both the novae and the recurrent novae. If we plot the logarithm of the mean period against the amplitude we find a linear relationship (Fig. 33) which was regarded as a strong indication of a close tie among these three classes of star.

More recent photoelectric and spectroscopic work has shown that the majority, if not all, of the dwarf novae are close binary systems in which a stream of gas is flowing from a cool, solar-type star to a white dwarf companion. In the case of U Geminorum, which is also an eclipsing variable, we now know that the outbursts are caused by unstable oscillations in the atmosphere of the cool component which result in excessive quantities of gas being ejected into the gas stream, thereby exposing the lower, hotter levels of this star. More recently, studies of SS Cygni indicate an opposite effect, namely that the white dwarf companion is responsible for the outburts. These two results are not necessarily incompatible since any increase in the amount of gas flowing from the cool star will almost certainly result in a raising of the surface temperature of the white dwarf due to the heating effect of this gas falling into this star.

The problem of elucidating the nature of these variables has proved to be an extremely difficult one for several reasons. Firstly, they are almost all extremely faint objects, even when at maximum, and observations during the minimum phase require the largest

possible instruments. Secondly, the close similarity between their light curves and the novae led astronomers to believe, even after the duplicity of these systems was discovered, that the nova-like outburst was closely associated only with the white dwarf component. Very few even considered the yellow star as a likely cause.

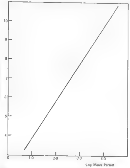


Fig. 33. *The period-amplitude relationship for the dwarf novae and recurrent novae*

The peculiar 'standstills' of the small Z Camelopardalis group are still not fully understood. Certainly there is no correlation between the length of a 'standstill' and the type of maximum which precedes it and there is absolutely no way of telling when such a period of quiescence will begin or end. The only clue we have at the moment is that of the dwarf novae which have been examined spectroscopically; those of the U Geminorum type have essentially circular orbits whereas RX Andromedae and possibly Z Camelopardalis appear to have highly eccentric orbits.

Table 8
DWARF NOVAE

Star	*Magnitude* *Max*	*Min*	*Mean Period (days)*	*Spectrum*	*Type*
RX And	10·3	13·6	14·1	Pec	Z Cam
UU Aql	10·6	16·2	56·0	Pec	U Gem
SS Aur	10·5	14·5	54·1	Pec	U Gem
Z Cam	10·2	13·4	20·0	Pec	Z Cam
SS Cyg	8·1	12·1	50·4	A1+dGep	U Gem
EY Cyg	10·9	15·1	40·8	Pec	U Gem
AB Dra	11·5	15·5	12·0	Pec	Z Cam
U Gem	8·8	14·4	102·9	Gep?	U Gem
IR Gem	10·8*	13·1*	75·0	Pec	U Gem
AH Her	10·6	13·9	19·6	Pec	Z Cam
VW Hyi	8·3	12·9	35·0	Pec	U Gem
X Leo	12·0	15·1	22·0	Pec	U Gem
AY Lyr	12·1	15·5	23·0	Pec	U Gem
BI Ori	13·2	16·6	24·6	Pec	Z Cam
CN Ori	11·8	14·7	19·2	Pec	Z Cam
CZ Ori	11·4	15·8	38·0	Pec	U Gem
RU Peg	10·0	13·1	70·0	Pec+dG3ep	U Gem
TZ Per	12·1	15·4	17·0	Pec	Z Cam
UV Per	12·3	15·2	300·0	Pec	U Gem
SU UMa	11·1	14·5	16·2	Pec	U Gem

*Photographic magnitude

A great deal of work has been carried out in recent years to investigate the possible evolution of these stars. All of the evidence we have points to the dwarf novae being close binary systems consisting of a white dwarf and a cooler G- or K-type star. Since the novae and recurrent novae have also been shown to be binaries, some astronomers are inclined to accept the view that there is a generic relationship between these stars. Somewhat more recently, evidence has accumulated to suggest that the precursors of the dwarf novae are the W Ursae Majoris eclipsing variables which have already been discussed earlier in the chapter. Briefly, it is thought that the slightly more massive component of a W Ursae Majoris system begins to evolve, growing larger in the process and ejecting mass into the system which is captured by the smaller companion. By the time the evolving star has reached the white dwarf stage it has lost sufficient mass for it now to be the less massive of the two and since the other star has now begun to evolve away from

the main sequence, the role of primary and secondary is reversed, as is also the direction of the flow of gas in the system. We thus have a white dwarf star and a cool, yellow dwarf with gas flowing from the latter which is exactly the sort of situation we find in the dwarf novae.

This relationship between the two classes of star is strengthened when we examine their distribution in space. The U Geminorum and Z Camelopardalis variables are not found concentrated along the galactic plane in the region of the Milky Way as the novae are. Instead, they belong to the galactic disc and their spatial distribution very closely resembles that of the W Ursae Majoris variables.

The Novae. With the exception of the supernovae which will be described later, and a small number of the long-period variables, the novae have the largest amplitudes of all variable stars. Not only are their light curves characteristic but their spectra show very well-defined changes following the outburst so that it is almost impossible to mistake them for any other kind of star. Several of these stars reach naked-eye brilliance at maximum as may be seen from an inspection of Table 9. The point must be made, however, that an even larger number are either binocular or telescopic objects and many undoubtedly escape detection altogether. Some indeed are only discovered long after maximum by careful comparison of patrol plates which are taken at regular intervals and cover the whole sky.

We must therefore recognise that novae are far more numerous than one might be led to believe from the comparative rarity of the very bright representatives of the class. From several considerations of the nova phenomenon it has been estimated that between twenty and thirty novae occur each year in the galaxy.

From a comprehensive study of the light curves of the known novae, it is possible to classify them into three main groups although even within each class there are wide variations in behaviour. Strictly speaking, it is best to treat each nova individually since the divisions between these three classes are by no means sharp or well-defined.

1. *The Rapid Novae*: these stars show an extremely steep rise to maximum which is followed by a fairly sharp decline that may then become shallower. In some cases the decline is marked by quite pronounced fluctuations, for example Nova V603 Aquilae (1918) and Nova GK Persei (1901) while in others, the decline is comparatively smooth as was the case for Nova XX Tauri (1927)

and Nova V476 Cygni (1920). The fast novae are generally regarded as those in which there is a decline of three magnitudes or more within 100 days of maximum. Although this is a purely arbitrary criterion it has proved useful in classifying these two classes. Fig. 34 illustrates the light curve of Nova GK Persei (1901) which may be compared with that shown in Fig. 35.

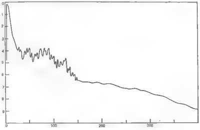


Fig. 34. *Light curve of Nova GK Persei (1901)*

2. *The Slow Novae*: unlike the rapid novae which have amplitudes of between eleven and thirteen magnitudes, those of the slow novae are somewhat smaller, usually being between nine and eleven magnitudes. A few of the slow novae, like Nova HR Delphini (1967) have even smaller amplitudes. This star has been identified as an object of 11·9 magnitude with an 09-type spectrum on patrol plates taken some years before the outburst. The amplitude, therefore, is one of only slightly greater than six magnitudes.

Applying the same criterion as before we can classify the slow novae as those in which the initial decline of three magnitudes takes longer than 100 days. The stay at maximum often lasts for several months and frequently there is a subsidiary rise following the decline to minimum. This is well shown in the light curve of Nova V732 Sagittarii (1936) illustrated in Fig. 35.

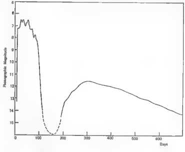


Fig. 35. *Light curve of V732 Sagittarii (1936)*

3. *The Ultra-slow Novae*: in general, the novae may be assigned to one or other of the above two classes. A few stars are known, however, whose light variations, although very similar to those of the novae, extend not over several months, but many years. The prototype of these stars – although not the first to be discovered – is RT Serpentis. Until 1909, this star was unknown being fainter than sixteenth magnitude. It then appeared on photographs of the region, brightening slowly until it attained magnitude 10·5 in 1919 where it remained until 1923. Following many fluctuations in brightness it finally declined to 13·3 magnitude in 1930 where it has remained ever since. Other stars of this type include V407 Cygni (1936) which only reached magnitude 14 at maximum, FU Orionis (1937), V939 Sagittarii (1914), and V941 Sagittarii (1910).

The most spectacular example, and the first to come to the notice of astronomers, is η Carinae. During the seventeenth and eighteenth centuries it was variously reported as between second and fourth magnitude but throughout most of the last century it underwent a truly remarkable sequence of fluctuations. At one time, in 1843, it

was as brilliant as Sirius (Fig. 36) and did not fall below naked-eye brightness until 1867.

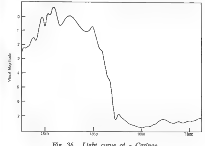


Fig. 36. *Light curve of η Carinae*

Both photographic and spectroscopic investigations indicate that η Carinae is a most peculiar object. Long-exposure photographs show the presence of faint nebulous condensations close to the star which are almost certainly due to a large circumstellar shell which is expanding at a rate of 480 kilometres per second. Material is being constantly ejected from the central star and from its distance of 6,400 light years, we must accept that it is both hot and large. Although it is not easy to make an accurate estimate of its mass, the latest figure is one of about 80 times that of the Sun.

We cannot yet say with certainty whether η Carinae is a very massive star which has evolved extremely rapidly, losing most of its hydrogen either by nuclear reactions or by constant ejection of material into the surrounding gaseous envelope, or an equally massive protostar which is still evolving towards the main sequence. In either event, it seems almost certain that such a body will be unstable and that these instabilities will be sufficient to produce the light variations which have so far been observed.

A word should be said here about the spectral type Q which is reserved for novae. In those rare cases where the pre-nova spectrum has been recorded, the star is generally of Type A or B (sometimes late Type O as was found for Nova Delphini). At maximum, the spectrum is continuous with the peak intensity far in the ultra-violet, often crossed by broad emission and absorption lines which, from the measurement of their Doppler shift towards the violet, provide us with the velocity of approach of the ejected gases.

Table 9
THE NOVAE

Star	Magnitude Max	Magnitude Min	Spectrum
Nova V603 Aql (1918)	−1·4	10·8	Q
Nova T Aur (1891)	4·4	15·8	Q
η Car (1843)	−0·8	7·9	cF5
Nova Q Cyg (1876)	3·0	15·2	Q
Nova V476 Cyg (1920)	2·0	15·4	Q
Nova HR Del (1967)	3·6	11·9	Q (09)*
Nova DN Gem (1912)	3·5	14·7	Q
Nova DG Her (1934)	1·3	15·4	Q
Nova Her (1960)	3·0	variable	Q
Nova Her (1963)	2·9	—	Q
Nova CP Lac (1936)	2·1	15·6	Q
Nova V841 Oph (1848)	4·3	13·1	Q
FU Ori (1937)	9·9	16·1	cF5
Nova GK Per (1901)	0·2	14·0	Q
Nova RR Pic (1925)	1·4	13·8	Q
Nova WY Sge (1783)	6·0	15·8	—
Nova V630 Sgr (1936)	5·3	15·2	Q
Nova Ser (1970)	4·6	13·6	Q
Nova CK Vul (1670)	2·7	17·0	—
Nova Vul (1970)	4·8	—	Q

* Pre-outburst spectrum

Gradually, the underlying continuum fades and the lines become wider and the bright lines of hydrogen in particular become more intense. As the star continues to decline, these emission lines fade and nebular bands appear, the spectrum eventually consisting of a faint continuum and strong Wolf-Rayet bands, indicative of a high surface temperature in the region of 35,000°C.

The Recurrent Novae. Mention has already been made of the fact that within the galaxy as a whole, some twenty or thirty novae occur each year. This being so, it follows that either all of the stars must have undergone a nova explosion in a time well within the age of the galaxy or, if only certain types of stars pass through the nova phase, such stars must explode on more than one occasion. If the latter is true, we would expect to find some stars in which the nova outbursts occur at longer or shorter intervals.

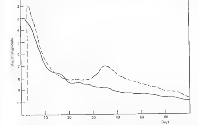


Fig. 37. *Light curve of T Coronae Borealis in 1866 (broken line) and 1946 (continuous line)*

Such recurrent novae are indeed known and are being increasingly studied by astronomers. As we might expect, the amplitudes of these particular stars are smaller than those of the true novae whose periods are measured in thousands of years and which have been observed at maximum on only one occasion.

In 1866, T Coronae Borealis rose rapidly from tenth to second magnitude in a manner characteristic of the novae. A rapid decline soon set in, however, and in a matter of a week or so it had fallen below sixth magnitude. A temporary revival to the seventh magnitude followed shortly after it had almost reached minimum but the star soon decreased in brightness again, falling to 9·8 magnitude

where it remained for eighty years with only minor fluctuations occurring of the order of half a magnitude. In February 1946, it rose once more to third magnitude, repeating its earlier behaviour almost exactly. The light curves of this star on both occasions (Fig. 37) show how closely the two maxima resemble each other.

Other recurrent novae are known which have been observed on three or more occasions within the past century. T Pyxidis has been seen at maximum in 1890, 1902, 1920, 1945, and 1965, while RS Ophuichi has erupted in 1901, 1933, 1958, and 1967. Although the light variations of the recurrent novae show many similarities to those of the novae, there are certain differences. The decline is normally more pronounced and quite often there are striking fluctuations during the fall to minimum. Almost certainly, the total amount of material ejected during the outburst is smaller than in the case of the novae and this may account for the steepness of the decline.

Table 10

RECURRENT NOVAE

Star	*Magnitude* *Max*	*Min*	*Spectrum*
T CrB	2·0	11·0	Q+gM3
HN Lyr†	10·5	(14·0	Q**
RS Oph	5·3*	11·5*	Ocp
T Pyx	7·0*	14·0*	Pec
WZ Sge	7·0*	16·1*	Pec
V1017 Sgr	7·2*	14·3*	Pec
U Sco	8·8	(17·6	Pec

* Photographic magnitude

† Some recent work indicates that this star may, in fact, be a long period variable with an M3e type spectrum.

Spectroscopic examination of these stars has revealed several interesting facts. T Coronae Borealis is a binary system consisting of a large red giant which is itself variable and responsible for the small-scale variations in brightness at minimum, and a blue dwarf star similar to those found in the old novae and the U Geminorum variables although considerably more massive. RS Ophiuchi, on the other hand, does not appear to be a binary star. Judging by its spectrum it seems far more likely to consist of a blue dwarf which is embedded within a gaseous shell since no Doppler effect has been detected in either the emission or absorption lines.

The Supernovae. We now come to a class of star which has only been distinguished from the ordinary novae during the last half century or so. Since their light curves are so similar to those of the novae, their true nature was not recognized for many years. In August, 1885, a star appeared close to the centre of the spiral galaxy M 31 in Andromeda which reached sixth magnitude before fading fairly rapidly in a manner typical of a nova. At the time no particular significance was attached to this star – S Andromedae – for nothing was then known of the distance of the galaxies. Indeed, there were many astronomers who considered it to be nothing more than an ordinary nova situated somewhere near the outer fringes of our own galaxy and merely seen in projection against the Andromeda spiral.

Then, in 1917, Ritchie began using the 60-inch and the newly-commissioned 100-inch reflectors at Mount Wilson to obtain some excellent photographs of the spiral nebula in Andromeda. Examination of the plates soon revealed the presence of several novae which, in every way, were like those found in our own galaxy, although being at a much greater distance they attained only about fifteenth magnitude when at maximum. Allowing for the distance of this galaxy – a little more than 2,000,000 light years – this corresponds to an absolute magnitude of – 6, again comparable with the 'normal' galactic novae.

Quite obviously, the star of 1885 belongs in a different catagory. At its brightest, it was roughly equal to the brightness of the galaxy itself. In other words, its luminosity was then equivalent to that of 100,000,000,000 suns!

In addition to this, the position of the star is well known from photographs taken during the years 1885 to 1887, and if it were a normal nova with an amplitude not exceeding thirteen magnitudes it should now be visible as a star no fainter than nineteenth magnitude. A search of long-exposure photographs which show stars down to magnitude 23, however, reveals no trace of it. If we assume that this star did indeed lie within the confines of the Andromeda galaxy, then its absolute magnitude at maximum must have been about – 17.

Once this was recognized, a systematic search of photographs taken of other galaxies soon revealed further novae of this kind and the name 'supernovae' was coined to describe stars which undergo these truly catastrophic explosions.

In general, the light variations of the supernovae are far less diverse than those of the novae. Nevertheless, Baade has been able

to distinguish two classes of supernovae, termed Type I and Type II. The main points of difference between the two are as follows:

1. *Type I Supernovae*: these stars possess high absolute magnitudes lying between − 14 and − 17 and have quite pointed maxima. Shortly after reaching maximum brightness, a rapid decline sets in which then becomes progressively slower. The spectra of these stars are quite distinctive, being dominated by lines of hydrogen and iron which show large Doppler shifts corresponding to radial velocities sometimes as high as 10,000 kilometres per second. One characteristic feature of the spectra is that the changes taking place do so with extreme regularity and also keep in step with the light variations. In the event of a Type I supernova being discovered only after maximum is past, it is therefore possible to calculate from the spectrum just when maximum brightness occurred.

2. *Type II Supernovae*: the maxima of these stars are much broader than those of the preceding type and although the initial fading may be quite rapid, this soon slows to be followed by a further rapid decline about 80 days after maximum. The absolute magnitudes usually lie between − 12 and − 13·5 being comparable with the novae in this respect. Their spectra, too, show marked similarities to those of the novae. Although the suggestion has been made that the Type II supernovae represent stars intermediate between the more extreme Type I supernovae and the ordinary novae, this must be accepted with a certain degree of reserve. The novae show a marked preference for the central galactic planes whereas the supernovae of both types may be found anywhere within the galaxies. Indeed, it seems probable that they tend to concentrate within the outlying regions rather than near the centre.

The Supernova Explosion. So far nothing has been said of the cause of the supernova explosion other than that it is far more catastrophic in nature than that of a typical nova. Supernovae have, of course, occurred within our own galaxy. The brilliant star which appeared within the constellation of Cassiopeia in October 1572 and which was closely observed by Tycho Brahe has been shown by Baade to have been a typical Type I supernova (Fig. 38). Photographic examination of its position as given by Tycho Brahe has so far failed to identify it with certainty and there seems little doubt that it is now fainter than eighteenth magnitude. At maximum it equalled Venus in brightness and from this we

must conclude that its amplitude was at least twenty-two magnitudes.

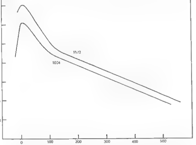


Fig. 38. *Light curves of the two galactic supernovae of 1572 and 1604*

A study of contemporary records indicates that the star which flared up in Ophiuchus in 1604 had a light curve also similar to a Type I supernova (Fig. 38). Here, photographs taken in red light with the 100-inch telescope have revealed the presence of a small nebulosity close to the position of the 1604 star, and there is very little doubt that this is the gaseous matter expelled during the supernova explosion.

The most outstanding example of a supernova remnant, however, is provided by the Crab Nebula. This object is unlike any other gaseous nebula, and both spectroscopic and photographic measurements show that this mass of gas is still expanding with a velocity of about 1,000 kilometres per second. From its present dimensions we may extrapolate backward in time to when the original outburst took place. This turns out to be about 900 years ago.

If we now examine ancient astronomical records we find that the Chinese astronomers observed a bright star in the position of the Crab Nebula in 1054. At maximum it was as bright as Jupiter, and as we know the Crab Nebula to be approximately 6,000 light years distant we may calculate the absolute magnitude of the supernova as -13. Close to the centre of the Crab Nebula is a very faint sixteenth-magnitude star which may be all that remains of the exploding star apart from the gaseous envelope itself. Recently, a pulsar has been discovered in this position and a good deal of evidence has now accumulated to show that such pulsars are the end product of a supernova explosion. It is, perhaps, interesting to note here that the Crab pulsar is the first to have been observed to pulse optically as well as sending out radio pulses.

Clearly, then, the total mass of the star expelled during a supernova explosion is much greater than that of a nova but the idea that the entire star is blown to pieces during the process is no longer accepted. The exact sequence of events leading to a supernova explosion is not yet known with certainty. This is to be expected, for not only are supernovae of much rarer occurrence than the novae but it is only comparatively recently that these stars have been subjected to detailed study. Some astronomers are of the opinion that the nuclear reactions going on within the cores of these stars eventually result in a catastrophic collapse which gives rise to an abrupt release of a tremendous amount of both nuclear and gravitational energy, the pressure of this flood of radiation ejecting most of the outer layers of the stars.

* * *

Other workers in this field, notably Schatzman, have argued that such stars become extremely unstable within their central regions, releasing a shock wave of great violence which travels at a high velocity through the external layers. Such a shock wave triggers off a sequence of nuclear reactions which result in the formation of heavy radioactive elements which in turn bring about the supernova explosion.

Here we may be tempted to ask: Is there any chance of a star such as the Sun becoming a supernova with disastrous consequences for the Earth and other planets? Astronomers are now reasonably certain that this will not occur. Only those stars in which the helium core exceeds 1·44 times the mass of the Sun, this figure being known as Chandrasekhar's Limit, can become supernovae.

Flare Stars. Over the past twenty years or so, several faint red dwarfs have been discovered which exhibit flare-like increases in brightness that are very like those which have been known for more than a century on the Sun. Owing to its high luminosity, solar flares produce a negligible change in brightness. Those of these intrinsically faint dwarf stars, however, are sufficient to bring about an appreciable variation in their brightness.

In 1924, Hertzsprung observed an abrupt rise of two magnitudes in a faint star in Carina and after ruling out the possibility that the star was an RR Lyrae variable with an extremely short period, he concluded that the rise may have been due to a fairly massive body of planetary dimensions falling into the star.

Hertzsprung's discovery appears to have been forgotten until December 1947 when Carpenter made a series of four-minute exposures of the red dwarf star L-756-8, now known as UV Ceti. When the plates were examined it was discovered that the star had brightened during this twenty-minute period by almost two magnitudes. The light curve showed certain similarities to that of a nova although the amplitude was much smaller and the rise to maximum even steeper. As with other astronomical discoveries of this kind, the finding resulted in a systematic search for similar flare-like activity on other faint red dwarfs in the neighbourhood of the Sun.

At the present time about a score of UV Ceti variables are known and their study has greatly increased our knowledge of the physical processes going on within their atmospheres. The flares on these stars are not only infrequent but generally amount to only half a magnitude or so. On at least one occasion, however, in September 1952, UV Ceti brightened from its normal magnitude of 12·9 to 5·8, remaining at this brightness for five minutes before the inevitable decline to minimum set in. Admittedly, this large increase in luminosity is rare but it does provide us with an indication of the highly unusual activity taking place within the atmospheres of these faint stars. The light curve of a typical flare of a UV Ceti variable is shown in Fig. 39.

Very few precise photoelectric determinations have been made of these flares and unfortunately the visual estimates do not allow us to define any minor irregularities which may be present, particularly on the descending branch of the light curve. The visual curves do, however, indicate that all of the flares are of a similar shape to that given in Fig. 39. The very steep rise to maximum is sometimes preceded by a slight increase in brightness just prior to the

main flare. Once maximum luminosity has been attained, the decline begins almost at once, and although there may be a secondary rise producing a distortion of the decline to minimum, this usually follows a fairly smooth exponential curve.

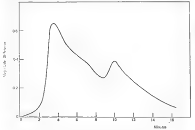


Fig. 39. *Light curve of AD Leonis*

Spectroscopic examinations have been carried out on several flare stars and here it is essential that we should differentiate between the spectrum of the star when it is at its normal magnitude and that obtained during a flare. Apart from the general faintness of these stars, it is comparatively easy to obtain a spectrum of the star when at minimum. Here it is found that all of these variables are M-type dwarfs showing emission lines of hydrogen in their spectra. Lines due to ionized calcium are also present. Many astronomers now accept that the presence of these emission lines in the spectrum of a red dwarf star indicates that it belongs to the UV Ceti class.

Obtaining a spectrum when the star is undergoing a flare-like outburst is not easy. Fairly long exposures are necessary to get satisfactory spectra and, since the duration of typical flare is measured in minutes, and the light changes are then both rapid and varied, we can generally only record an average spectrum of the variations which are taking place. It appears from the scanty data

available that two distinct series of spectroscopic changes take place during a flare. Firstly there is an intense ultra-violet continuum superimposed upon the spectrum in this region which completely blankets the normal absorption features. At the same time, the emission lines of hydrogen increase in intensity and there may even be emission lines of neutral and ionized helium in the spectrum. Secondly, although the underlying continuum remains essentially unaltered, the lines of hydrogen increase in strength, those of ionized calcium remaining virtually unchanged.

The exact nature of these flares is still a matter of conjecture and many more observations are needed before the final answer is found. It does seem, though, from the present evidence that they are not due to a sudden heating of the stellar atmosphere. Most of the observed flares last only for a matter of minutes and it is difficult to postulate any mechanism whereby a large mass of gas can cool down by more than two thousand degrees in so short a space of time. The most plausible suggestion is that due to Askanjan. On this theory, a sudden, large increase in radiation is brought about by a release of energy from the deeper levels of the star. The energy released emerges through the upper atmosphere where it is transformed into radiation by a non-thermal process. When this energy is released deep within the star, the resulting increase in brightness amounts to only a quarter of a magnitude or so. The much more infrequent flares with larger amplitudes are due to the release of energy taking place within the higher levels.

From a study of the distribution of these variables in space it now seems that the Sun lies close to the centre of a cloud of UV Ceti stars. Within a sphere having a radius of 100 light years from the Sun, no UV Ceti stars have been found beyond 65 light years. Naturally, we may argue that this is not a real effect but is due entirely to the intrinsic faintness of these variables. There is, however, further evidence to indicate that flare stars form in large, physically-connected clusters.

One of the characteristics of such stellar associations is the high proportion of binary systems which they contain. When we come to examine the known UV Ceti variables we do, indeed, find that more than 60 per cent of them are members of close binary systems.

Before leaving the subject of flare stars, mention must be made of the radio emission we receive from these particular variables. More than a century ago, Carrington and Hodgson observed a series of flares close to the centre of a group of sunspots and were

able to correlate them with a weak magnetic disturbance which occurred on Earth almost simultaneously. Some fifteen hours after the flares were observed, a very violent magnetic storm broke out which continued for six days. The weak disturbance is caused by radiation travelling at the velocity of light while the much more intense storm is due to a stream of electrons moving at a lower velocity.

Table 11
FLARE STARS

Star	Magnitude Max	Magnitude Min	Spectrum
YZ CMi	10·3	11·6	dM4·5e
DH Car	13·1	14·9	dM4·5e
V645 Cen	10·3	11·3	dM5e
DO Cep	9·9	11·4	dM4·5e
UV Cet	5·8	12·9	dM5·5e
EV Lac	8·2	10·2	dM4·5e
AD Leo	9·0	9·5	dM4e
V371 Ori	9·9	11·7	dM3e
EQ Peg	11·0	11·3	dM4e
V1216 Sgr	10·1	10·5	dM4·5e
WX UMa	13·1	14·8	dM5·5e
BD +1° 1522	8·8	9·5	dK2e
BD +33° 1646	10·9	11·1	dMe
BD +51° 2402	5·8	8·3	dK6e
BD +55° 1823	9·6	10·1	dM1·5e
BD −21° 6267	9·8	10·2	dM4·5e
BD −32° 16125	12·1	12·5	dM3e
Ross 154	10·0	10·5	dM4·5e
Ross 867	12·4	13·4	dM5e
Wolf 47	13·1	13·7	dM3e
Wolf 359	12·5	13·5	dM6e
Wolf 424A	10·7	12·7	dM5·5e
Wolf 1130	11·6	12·2	dM3e

All of the above magnitudes are photographic

If we go on the assumption that the flares of the UV Ceti variables are similar in nature to solar flares, clearly those which have amplitudes of a magnitude or more must be due to even more violent activity within the stellar atmosphere. The question therefore arises as to whether there is any detectable radio emission

from these stars. This is an extremely important question for if we can correlate radio emission with visual flares, it will provide us with valuable information concerning the ejection of high-energy particles into interstellar space.

Several radio observatories are now actively engaged in this research, co-operating closely with visual observers. The Radiophysics Laboratory at Sydney, Australia, for example, and Jodrell Bank in England have programmes covering several of the flare stars. The results obtained so far are not conclusive for on several occasions when bright flares have been observed on UV Ceti, no radio emission has been detected. On the other hand, radio emission at 3·5 metres followed by an extremely powerful burst at 15 metres has been observed at the times of three probable flares on this star. The interval between the two emissions was similar to that found for a typical solar flare.

Secular Variables. A small number of the brighter stars are known which appear to have undergone changes in brightness over a period of many hundreds of years. The records upon which evidence of their variability is based are, for the most part, extremely scanty and often unreliable. Nevertheless, a few of them have been found to exhibit small variations in brightness and it would be unwise to discount all of the estimates, many of which were made two thousand years ago by Hipparchus and Ptolemy. The star Pleione in the Pleiades was estimated by Ptolemy to be comparable in brightness with its close neighbour Atlas whereas now it is almost two magnitudes fainter.

In the Almagest both θ Eridani and β Leonis are recorded as being of first magnitude, and other stars which, accepting these early estimates, have apparently faded by similar amounts during the intervening period are β Librae and δ Ursae Majoris.

Certain other bright stars are known which seem to have brightened by comparable amounts, for example β Canis Majoris and α Ophiuchi. The former star is known to be variable but the amplitude is extremely small, only about 0·1 magnitude and this certainly cannot account for the pronounced secular fading.

At present it is very difficult to account for these changes in brightness on the assumption that they are real. Pleione does have certain features which suggest that it may be a shell star like P Cygni, but an investigation of the position of Pleione on the Hertzsprung-Russell diagram shows quite clearly that it has begun

evolving away from the main sequence, and since such evolving stars become both larger and brighter during this evolutionary phase it would be expected that Pleione should have become brighter and not fainter.

CHAPTER 3

Methods of Observation

In the previous chapter we have been concerned with a survey of the many different classes of variable stars and very little has been said about the methods of observing them. Here we must consider the main work of the observer, namely that of finding the variable from the charts, making an accurate estimate of its brightness and recording the results. The actual drawing of the light curve and derivation of information from it will be left to a later chapter since, unless the observer is fortunate enough to be able to observe on a sufficient number of nights throughout the year, there will inevitably be wide gaps in the run of observations. There is also personal error to be taken into account, especially where visual estimates are concerned and here the best light curve will be that compiled from a large number of observations made by several observers. The object of variable star observation is therefore threefold. Finding the variable, making as accurate as possible a determination of its magnitude, and reporting the results in a manner suitable for subsequent use.

Finding the Variable

Planetary observers have one advantage over variable star observers in that there is seldom, if ever, any difficulty in finding the object to be observed. Where variable stars are concerned, it must always be remembered that the variable may be invisible at the time and the problem becomes one of finding the appropriate star field, rather than the star itself. Fortunately the human eye is extremely adaptable to the recognition of patterns and the main difficulty encountered by observers, particularly those new to this branch of astronomy, is that of visualizing the *scale* of the field. This, of course, is dependent upon the magnification used and it is helpful to know this beforehand.

The charts issued by the American Association of Variable Star Observers for each variable are drawn to the following scale:

Chart (a) – 5′ = 1 mm;
Chart (b) – 60″ = 1 mm;
Chart (c) – 40″ = 1 mm;
Chart (d) – 20″ = 1 mm; and
Chart (e) – 10″ = 1 mm.

In general, the (a) and (b) charts are given with North at the top as seen in binoculars, the remainder being inverted for telescopic observation. The large-scale (a) charts give the position of the variable in relation to several naked-eye stars and are normally used with binoculars (when the variable is sufficiently bright) or in conjunction with the finder telescope as a rough guide to the position of the field.

As far as the Variable Star Section of the British Astronomical Association is concerned, a similar method is adopted and in many cases the charts are adapted from those just mentioned. In this case, the charts normally cover 9°, 3°, 1° and 20′ fields for each variable. In some instances where the star is particularly faint at minimum and more comparison stars are required, 10′ and 5′ charts are issued. Each set of charts is also accompanied by a list of comparison stars and their adopted magnitudes. Unlike the A.A.V.S.O. charts where the magnitudes of the comparison stars are marked on the charts (to the nearest tenth of a magnitude) with the decimal point being omitted, the comparison stars used by the V.S.S.B.A.A. are marked by a letter or number on the charts and a sequence of magnitudes is issued with the charts.

There are several ways in which the field of the variable may be located. Where the observer has an equatorially-mounted telescope fitted with divided circles and possibly a driving clock it is possible, by making the necessary calculations, to set the instrument directly upon the field. This, however, can be a tedious and time-consuming operation and is quite unnecessary except, perhaps, in the case of very large telescopes. Very often, an altazimuth mount proves more convenient than the equatorial type since it is easier to swing the instrument from one part of the sky to another.

In the case of a telescope with an equatorial mount it is sometimes advantageous to locate a bright star at approximately the same Right Ascension or Declination as the variable and then find the field by sweeping slowly in the appropriate direction. A similar technique, known as 'drifting,' may be used with an altazimuth mount. Here a bright star of the same Declination is chosen, one which also precedes it so that by allowing the stars to drift across the field for the correct length of time, the field of the variable should then be visible in the telescope. When this method is used it is advisable to employ as low a power as possible in order to have a sufficiently large field of view.

It is, of course, necessary to have a good working knowledge of the naked-eye stars and a star atlas giving the position of stars down to the sixth magnitude is essential. The procedure for using the charts to find the variable is the same for both the A.A.V.S.O. and the V.S.S.B.A.A. series. The (a) or 9° charts will show the position of the variable with respect to several bright stars and one or more of these may be sufficiently close to the variable to appear in the same field using a low power. The comparison stars, those which are known to be constant in brightness and whose magnitudes have been accurately determined, are marked on the charts as previously described. Those closest to the variable on the (a) or 9° chart will also appear on the next in the series which will include several fainter comparison stars. In turn, the next chart will show several of the nearer guide stars and so on through the series. The method, therefore, is to proceed step by step from the brighter stars on the (a) or 9° chart to the (e) or 20′ chart, each successive step both narrowing the field and introducing fainter comparison stars. Once the pattern of stars around the variable has been recognized it is advisable to return to it several times as an aid to future identification. Quite often the variable will be at the limit of the observer's telescope and here it is an advantage to use a higher power since this tends to darken the field, making the stars themselves relatively brighter. Averted vision also helps for although the centre of the eye is more sensitive to differences in colour, the outer area of the retina is more sensitive to light.

Use of Instruments. The various instruments used by the variable star observer have been fully described in Chapter 1 and will not be gone into in detail here. We saw there that the main requirements are light grasp (which is theoretically proportional to the square of the aperture) and the resolving power (which is proportional to the aperture). The magnification which depends solely upon the focal lengths of the objective and the eyepiece is only of secondary importance where stellar work is concerned.

Where the stars are excessively bright, uncertainties can be introduced when estimating the relative brightness of comparison stars and the variable. When observing conditions are good with no interference from moonlight, stars down to the fourth magnitude are best observed with the naked eye. Those between fourth and eighth magnitude may be observed either with binoculars or the finder of the main telescope. A small refractor of two inches aperture is also very useful for stars in this range of brightness, particularly if it has a short focal length.

Below eighth magnitude we come into the purely telescopic range and quite naturally, the larger the aperture, the more variable stars it is possible to observe. A 6-inch reflector, for example, will show far more variables than one observer can possibly observe. A word of caution is necessary here, however, for many beginners tend to use large apertures when observing the brighter stars in the telescopic range. As mentioned earlier, this can often lead to very discordant results and the newcomer may become discouraged when his estimates disagree with those of other, more experienced, observers. With experience it will be found that there is an optimum light-gathering power for any given magnitude and the best rule to apply is to adjust the aperture, by the use of stops if possible, so that the brightest star in the field is about three magnitudes brighter than the faintest which can be seen. This is particularly the case when observing red stars such as the long-period and semi-regular variables.

The Purkinje Effect. It is an established fact that observers differ quite appreciably in their sensitivity to red light, more so than to any other colour. In addition to this, however, the so-called Purkinje Effect has to be taken into account when estimating the brightness of red stars. If we have two point sources of light, one of which is red and the other white, both of the same brightness and then reduce each by the same amount, it is found that the red source is now the fainter of the two. Conversely, the red source appears the brighter if we increase them by an equal amount. This is because the eye becomes more sensitive to radiation of a shorter wavelength as the source is decreased in intensity. Undoubtedly the wide scatter of estimates made by different observers of red stars when using similar instruments is due to this effect.

Unfortunately it is not easy to reduce these discrepancies among observers and virtually impossible to eliminate it altogether. As far as the long-period and semi-regular variables are concerned we inevitably have the situation where we are comparing a red variable with white or yellow comparison stars. One might argue that we should compare such variables with red stars but since almost all red stars are variable to a certain extent this is not practicable. The use of coloured filters to obtain uniformity of visual estimates proves of little value and has the undesirable effect of reducing the amount of light available.

The point has already been made that it is the central portion of the eye which is susceptible to changes in colour and accordingly, one way of minimizing the effect is to allow the eye to wander around the red star and the comparison in turn and not to stare directly at either. This method only goes part of the way to solving the problem, however, since the outer part of the retina is relatively insensitive to red light and one tends to estimate the variable fainter than it actually is. The best way of all is to use a smaller instrument when red stars are bright or to employ stops to reduce the aperture and, incidentally, to flatten the field.

Colours of Variable Stars. It is often quite helpful to note the colour of variable stars throughout the various phases of their light cycles. This applies particularly to the novae and the long-period variables.

The following scale is generally used by variable star observers for estimates of colour:

0. Pure white
1. Yellow-white
2. Pale yellow
3. Pure yellow
4. Deep yellow
5. Pale orange
6. Orange
7. Deep orange
8. Red-orange
9. Red with a trace of orange.
10. Pure red

It is very doubtful if 9 is ever observed and 10 is never seen unless the telescope used is not perfectly achromatic. Since observers differ widely in their sensitiveness to red, estimates between 6 and 9 on the above scale must not be considered as giving an exact representation of stellar colour, especially if half-division estimates are made. Furthermore, such estimates of colour should never be made unless the sky is perfectly dark and clear and there is no moon. It is not generally realized that the night sky is redder than the day sky which is relatively richer in the blue and yellow wavelengths. The fact that the opposite appears to be the case is a further example of the Purkinje Effect.

If colour estimates are made of the long-period and semi-regular variables it will be found that whereas those stars having spectra of types N and R become progressively redder as they fade, the same is not true of the M and S variables. The reason for this is to be found in their spectra. The spectra of the N and R types contain absorption bands due to carbon compounds which absorb strongly in the blue end of the visible spectrum. As these stars fade, these bands increase in intensity, blotting out more and more of the blue portion of the spectrum so that during the faint phase the red end predominates.

In the M and S type variables, on the other hand, the absorption bands are due to titanium and zirconium oxide respectively which absorb in the red end of the spectrum and if anything, the star becomes slightly bluer as it fades although this effect is so small that it is doubtful if it ever becomes really noticeable.

The colour changes in the novae are usually quite distinctive. At maximum, these stars are white, the colour changing slowly through yellow to red as the decline sets in. Later, as the nova continues to fade, the colour becomes more orange and finally a leaden-blue as it approaches minimum.

Most of the other classes of variable star are white or yellow throughout most of their light cycles although certain of the RV Tauri type are reddish during their deep minima when their spectra closely resemble those of the M-type long-period variables. The only other group which, being red dwarfs with M-type spectra, are red in colour are the flare stars, the UV Ceti variables.

Estimation of Brightness

Once the variable has been located, it is then necessary to make an estimate of its brightness. This may be done in several ways – visually, photographically, photovisually, photoelectrically, or bolometrically. Of these, the latter does not concern us here since this is a very specialized technique requiring equipment which is unlikely to be in the hands of the amateur observer. Let us now take each of these methods in turn and examine them in detail.

Visual Estimates. For each variable, a list of comparison stars with their adopted magnitudes is drawn up and the variable is compared with at least two of these stars if possible. The comparison stars are chosen so that the difference in magnitude between any two of them in the sequence should preferably not exceed half a magnitude. In certain cases, of course, this may not be possible

owing to a lack of suitable stars but in any event the difference should not be greater than one magnitude otherwise uncertainties will be introduced into the estimate. Where more than two comparison stars are available which are similar in brightness to the variable, it is useful to use these as a check on the first estimate. Two methods are in general use, particularly by the V.S.S.B.A.A.

The Fractional Method: this is the more suitable method for the beginner since, as we shall see later, the Step Method requires that the eye should be trained to distinguish in steps of 0·1 magnitude and this can only come with months of practice. Two comparison stars are chosen, one a little brighter than the variable and the other slightly fainter. The brightness of the variable is then mentally estimated as a fraction of the interval between the two comparison stars. To do this, the observer divides the interval into a number of equal parts, for example 2, 3, 4, 5, or 10 and estimates the number of these parts by which the variable is fainter than one star and brighter than the other. There is no need at this stage to know the magnitudes of the comparison stars, this comes later when the light estimate is converted into the deduced magnitude.

As an example, let us suppose that the two stars chosen are designated A and B, with A being the brighter of the two. Let us also assume that the number of parts into which the interval has been divided is four. Then, if the variable appears to be one part fainter than A and three parts brighter than B, the record will be given as 'A(1)v(3)B', the brighter star always being recorded first. The letter 'v' is quite sufficient to denote the variable since the designation of the star itself will be given at the top of the observation sheet.

On certain occasions, when the variable is either exceptionally bright or extremely faint, it may be impossible to place the brightness of the variable between two comparison stars. This will be the case if the variable is brighter or fainter than any of the comparison stars given in the sequence. In this event, two stars should be chosen, both of which are either fainter or brighter than the variable. Let us now consider each case in turn. If the variable is brighter than both stars and it is estimated to be brighter than A by a quarter of the amount by which A is brighter than B, then we record this as 'v(1)A(4)B'. If, at the other end of the scale, we consider the variable to be fainter than either of the comparison by, say, a quarter of the interval between them, we write this as 'A(4)B(1)v'.

Finally, there are two other cases which we must consider. It may be that on occasion the variable is considered to be exactly equal in brightness to a comparison star and will be recorded as, say, '=C'. Whenever this is so, an additional check should be made, if possible, using other stars which are brighter and fainter than the variable. The last possibility is that the variable is not visible at all in the observer's instrument. This does not mean that no observation should be made. The observer should then determine the faintest comparison star which can be seen with certainty. If this is, say, star T in the sequence, the record will read 'v<T'. Such negative observations can be extremely valuable, particularly in the case of the irregular variables such as the U Geminorum and Z Camelopardalis stars since other observers may be unable to observe on that particular occasion owing to bad weather conditions and negative estimates provide information on whether or not a maximum has been missed.

Pogson's Step Method: this method has certain advantages over the Fractional Method just outlined. The variable is compared with only one comparison star at a time and this also enables the observer to detect variability in a comparison star which might not otherwise be found. It can also be useful as a check on the adopted magnitudes of the comparison stars since instances have been known where the wrong magnitude has been assigned to a star in the sequence.

It is not, however, recommended for the beginner since the eye must first be trained to estimate in tenths of a magnitude and very often this is not the observer's own 'natural' step. To become proficient at this method, the observer must first check on the magnitudes of several comparison stars in order to recognize differences in magnitude of one-tenth, two-tenths, three-tenths and so on. Steps greater than half a magnitude should not be used as these cannot always be relied upon. If possible at least two, and preferably more, comparison stars should be used unless the Fractional Method is employed at the same time. Where both methods are used together but only one comparison star has been employed for the Step Method, it is advisable to give double-weight to the Fractional estimate.

Deducing The Magnitude From the Light Estimate. Having made a visual estimate of the brightness of the variable by either of the two methods just given, we must now derive the magnitude. Let us assume that the magnitudes of the two comparison stars

which have been used are A=8·44, and B=8·93. Then the interval between them is 0·49 magnitude.

In the first example given above, the observer estimated the variable as 'A(1)v(3)B', dividing the interval into four equal parts. Each fraction is therefore 0·12 magnitude and adding this to 8·44 gives 8·56 as the magnitude of the variable. The same result is obtained by subtracting three-quarters of 0·49=0·37 magnitude from 8·93.

In the second case where the light estimate was 'v(1)A(4)B' and the comparison stars have the same magnitude as before, we have:

v is $0{\cdot}49 \times \frac{1}{4} = 0{\cdot}12$ magnitude brighter than A.

Since A is 8·44, we subtract 0·12 giving 8·32 magnitude for the variable.

Similarly, when the variable is fainter than both A and B, the light estimate being 'A(4)B(1)v':

v is $0{\cdot}49 \times \frac{1}{4} = 0{\cdot}12$ magnitude fainter than B.

As B is 8·93, we must add 0·12 giving 9·05 magnitude for the brightness of the variable.

Let us now examine the case where, in addition to estimating the variable as 'A(1)v(3)B', the observer has also used Pogson's Step method employing two stars, C =8·32 and D =8·78 magnitude. Here we shall assume that the observer estimates the variable as three steps fainter than C and two steps brighter than D. This is then recorded as

C−3, D+2.

Reducing these observations to magnitudes we obtain:

C−3=8·62
D+2=8·58 The mean is therefore 8·60 magnitude

Combining the two estimates we have:

A(1)v(3)B= 8·56
C−3, D+2= 8·60

Total=17·16
Mean= 8·58=deduced magnitude.

Photometric Estimates. The methods of determining magnitudes photographically and photoelectrically are dealt with in detail in Chapter 9. Here we shall only concern ourselves with the estimation of brightness photometrically.

When the visual estimates of several observers are examined, it soon becomes apparent that for the long-period and semi-regular variables, there is quite a wide scatter about a mean value. The fact that these individual deviations from the mean are smaller in the case of white and yellow variables provides a strong case for the Purkinje Effect being the cause of the variations. In many cases, two observers can differ by as much as one or two magnitudes in their estimate of a long-period variable on the same night and under similar conditions. In drawing the light curves of these stars the means of the various estimates are taken giving the average curve. Quite often, too, it is possible to determine each observer's average deviation from the mean and one may be classed as either a bright or a faint observer of red stars. These differences found between various observers when estimating the brightness of stars of different colours are known as their colour equation.

When it comes to making accurate determinations of the magnitudes of the comparison stars, however, it was soon recognized that

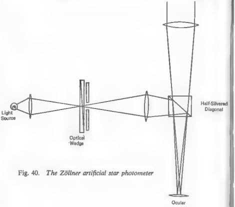


Fig. 40. *The Zöllner artificial star photometer*

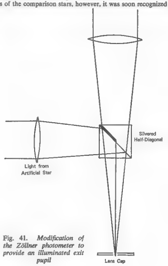


Fig. 41. *Modification of the Zöllner photometer to provide an illuminated exit pupil*

purely visual observations were not sufficiently accurate or uniform. Most of the magnitudes used for sequences of comparison stars have been determined photometrically and tied in with the North Polar Sequence which is a series of stars in the vicinity of the north celestial pole whose brightnesses have been determined with the greatest possible precision. These are the standards against which all other magnitudes are measured.

One of the simplest and most useful photometers is the Zöllner artificial star photometer (Fig. 40) which can be readily adapted to provide an illuminated exit pupil (Fig. 41).

In the original form the light from an electric filament is focused upon a pinhole in front of which is placed an optical wedge.

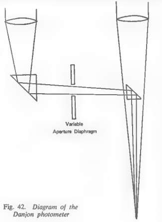


Fig. 42. *Diagram of the Danjon photometer*

The image of the pinhole is then projected into the eyepiece by means of a second lens and reflection from a half-silvered diagonal. This forms the artificial star which can be varied in brightness by means of the optical wedge. This arrangement shows the artificial star beside the variable in the same field and the wedge is adjusted until both images are of equal brightness. To modify the photometer to give an illuminated exit pupil, the half-silvered diagonal is replaced by one, only half of which is silvered. The eyepiece, in this case, is not used, a simple lens cap being employed instead. Here, the optical wedge is rotated until both halves of the field are equally illuminated. Zöllner photometers were used extensively between 1880 and 1915 to measure the brightness of more than 50,000 stars in the northern and southern hemispheres which formed the basis of the Harvard catalogues of stellar magnitudes.

One other type of instrument is worth mentioning here since it is particularly suitable for the observation of variable stars. This is the Danjon photometer (Fig. 42) in which the variable is viewed directly while the image of the comparison star is projected into the same field by the use of two silvered prisms. Between the prisms is situated a square diaphragm, the aperture of which can be adjusted. To measure the brightness of the variable, the aperture of the diaphragm is opened or closed until the two images are equal in brightness. The difference in brightness between the comparison and the variable is then calculated from the length of the diagonal of the aperture which is measured accurately by means of a micrometer.

Both the Zöllner and the Danjon photometer are capable of increasing the accuracy of visual determination of magnitudes. The accuracy attainable by purely visual means can, with experience, be within 0·1 to 0·2 magnitude. With the additional aid of a photometer, this may be increased to within about 0·02 magnitude.

Source of Error

In a comparatively short time, the beginner will find that there are few difficulties associated with either finding the field of the variable or in making a satisfactory light estimate. Provided he sticks by the simple rules, his observations will be sufficiently accurate to enable a good light curve to be drawn. There are, however, certain sources of error of which he must be aware and try to avoid as much as possible. These are dealt with under the following headings:

1. *Misidentification of either the variable or a comparison star*: even when the star field has been correctly identified, it is sometimes possible to wrongly identify the variable, especially when it is faint and near the limit of observation. Where a faint star exists close to the position of the variable, this may easily be mistaken for the variable itself if the latter is not visible at the time and it is only when the variable begins to rise to maximum that this is recognized.

Trouble experienced in recognizing the correct comparison stars may arise from two causes. Firstly, the observer may not be sufficiently familiar with the field and frequent consultation of the charts at the telescope is unwise since, as we shall see, the repeated use of a light of any kind tends to dazzle the eye and destroy dark-adaptation. Secondly, the comparison star may be very close to another, possibly of about the same magnitude, thereby causing some confusion. Although the sequences of comparison stars are chosen, wherever possible, so that they are reasonably distant from their neighbours, this cannot always be done. Both of these difficulties will eventually be overcome as the observer grows more familiar with the star field.

2. *Adaptation of the eye to darkness*: it is not readily appreciated how long it takes the average eye to become adapted to the darkness after leaving a lighted room. At least ten minutes should be allowed for the eye to become accustomed to the darkness of the night sky. When observing a variable for the first time it will certainly be necessary to refer occasionally to the charts while at the telescope. A faint red light is the best to use but even under these conditions, two minutes should be allowed to elapse before continuing to observe.

3. *Colour perception and the Purkinje Effect*: this has already been discussed but owing to its importance in the study of so many red variable stars it is worth while restating the two methods of reducing this effect even though it may prove to be impossible to eliminate it entirely. A large aperture should not be used for observing red stars when these are excessively bright. The main telescope should either be stopped down or a smaller instrument used. Staring at the variable should also be avoided. It is far better to take several quick glances, switching the variable and the comparison star alternately to the centre of the field of view. As an experiment, the observer may keep his attention fixed upon a red star in the telescope for half a minute or so. It will then be

found that the star appears to increase in brightness in a series of small jumps. One further example of this may be encountered if the observer has been following a bright red star for some time with the main instrument and then changes abruptly to either the finder or binoculars. Almost invariably, it will be discovered that the deduced magnitude shows a sharp jump at the time the changeover was made.

4. *Atmospheric absorption*: absorption of starlight due to the atmosphere is generally considered to be zero at the zenith, gradually increasing with decreasing altitude. This is not, of course, strictly accurate. The true brightness is that which we would observe from outside the atmosphere and certain such observations have been made by orbiting telescopes. Calculations have shown that for a star at the zenith, the true brightness is reduced by about half a magnitude. This represents the absorption due to the minimum mass of air through which it is possible to view the stars from the surface of the Earth.

A star at an altitude of only 30° is observed through an air mass about twice as thick as when seen at the zenith and the corresponding absorption is therefore one magnitude.

We may therefore write the following simple equation:

$$M = M_o + 0{\cdot}5A \qquad (1)$$

where M is the observed magnitude, M_o is the true magnitude where no atmosphere is present and A is the mass of air through which the star is observed taking that at the zenith as unity.

It is clear, therefore, that atmospheric absorption becomes quite a serious problem when observing variables which lie close to the horizon. Tables giving the necessary correction to apply for different altitudes are available but it must be remembered that, if they are used at all, the figures apply only when the sky is both clear and uniform.

When it is necessary to determine magnitudes with a high degree of accuracy, for example in the case of comparison stars, eclipsing variables, or those stars with small amplitudes, one further correction must be taken into account. To illustrate this we may take a very well-known phenomenon. When the Sun lies close to the horizon, it will be noticed that it appears redder than when near the zenith. This is due to the fact that the atmosphere absorbs blue light more efficiently than red. Consequently, the atmosphere will absorb slightly more of the light from a blue star than a red one. In other

words, the amount of atmospheric dimming depends, not only upon the mass of air through which the light travels, but also upon the colour of the star.

Whereas equation (1) would be accurate for a long-period variable of spectral type M, the corresponding equation for a B-type comparison star would be:

$$M=M_0+0{\cdot}57A \qquad (2)$$

Let us now take an extreme case and see how this effect will alter the accuracy of our estimates. Suppose we have two stars lying close together at an altitude of only 10° above the horizon, one a star of spectral type M and the other of spectral type B. At this altitude, the value of A is approximately 2·5. We shall also assume that as seen from outside the atmosphere both stars would be considered as equally bright. In other words M_0 is the same for both.

Then from equations (1) and (2), the red star will appear to be 0·18 magnitude brighter than the blue star when viewed from the surface of the Earth. Obviously it is difficult, if not impossible, to standardize on the magnitudes of comparison stars of different spectral types to an accuracy better than 0·2 magnitude. Although it is possible to allow for the effect of altitude by choosing stars which are at the same altitude, the task of making allowances for the differences in colour is not so easy.

With most variables, an accuracy of 0.2 magnitude is quite acceptable and with red stars, discrepancies of this order are overshadowed by the Purkinje Effect. Even in these cases, it is better to use only one comparison star which is at about the same altitude than to rely upon estimates made using two or more stars which are at some distance above or below the variable.

5. *Bias*: this is a source of error which can result in wide discrepancies in an observer's estimates. Over-observing of a variable, particularly those of the long-period, semi-regular, and R Coronae Borealis type can lead to bias. In the case of the long-period and semi-regular variables, the effect is most clearly seen when a hump is present on one of the branches of the light curve. Very often it will be found than an observer records the star as continuing to brighten or fade for some days after it has actually been at the same magnitude due to the presence of such an irregularity in its light fluctuations.

The R Coronae Borealis stars present another aspect of this. As we have seen, these stars remain at maximum for an unpredictable

length of time and then commence to fade without warning. Owing to bias, the observer may not be aware that the star has begun to fade for some days after fading has commenced, by which time it will appear to have dropped by some two or three magnitudes in a single day or so.

From what has just been said it will be clear that bias is due to the observer unconsciously extrapolating from his recent estimates and assuming that the star will behave in a certain manner based upon his knowledge of its past behaviour. When dealing with these types of star it must be recognized that not only do marked irregularities occur at almost any point on the light curve but in the case of the irregulars and long-period variables they must be expected. One must *never* assume that because a long-period variable or semi-regular star has been brightening or fading slowly and fairly regularly over a few weeks that it will continue to do so until maximum or minimum is reached. There are quite likely to be prolonged periods during which it remains virtually stationary in brightness.

Since bias is an unconscious attitude on the part of the observer it is quite impossible to eliminate it entirely. If possible, the previous estimates and the magnitudes of the comparison stars should be forgotten, or at least ignored. One should not, perhaps, be dogmatic about the optimum frequency of observing the various types of variable star in order to reduce the effect of bias. The irregulars such as the R Coronae Borealis, U Geminorum, Z Camelopardalis, and the nebular variables must, of course, be observed on every possible occasion since their light variations are both rapid and unpredictable. The same applies to the novae.

Since they change in brightness much more slowly, the long-period and semi-regular variables may be satisfactorily observed two or three times a week depending upon the observing conditions. One exception to this is when a negative observation has been obtained, often due to haze or moonlight, and improved conditions on the following night enable a positive observation to be made, otherwise it is unwise to make estimates of such stars on two or more consecutive nights.

6. *Position angle*: the ideal method of comparing the variable with a comparison star is to bring each in turn to the centre of the field of view. Unfortunately, with large telescopes this is not always practical, particularly when two directions of motion are involved. In this case it is necessary to choose the lowest suitable power and comparison stars sufficiently close to the variable to allow the eye

to move quickly from one to the other. By so doing, however, we introduce a further source of error which depends upon the position angle between the two stars. It is now recognized that of two stars of equal brightness in the field of view, that which is lower in the field, or which lies towards the observer's nose, usually appears the brighter. If both eyes are equally trustworthy one may observe with each eye alternately thereby reversing the respective positions of the stars and also by turning the head slightly.

7. *Averted vision*: when a star lies at the threshold of visibility it is necessary to use averted vision in order to detect it. So long as both the variable and the companion star are observed by averted vision little error, if any, is introduced. Large errors will, however, be made if one compares the variable with a comparison star on the very edge of the field, particularly since the latter will almost certainly be out of focus. It must be remembered, of course, that since the outer regions of the retina are relatively insensitive to red light, a star of this colour will tend to appear fainter than it really is when observed by averted vision.

8. *Miscellaneous factors affecting accurate estimates*: in addition to the above, several other factors have an effect upon the accuracy of an observation. Haze, patchy cloud, and moonlight all add uncertainties which are sometimes difficult to estimate. Mental and physical fatigue which often come at the end of a long observing session both tend to impair one's judgement. The same may be said of uncomfortable posture which is often encountered when viewing stars near the zenith, especially with refractors of long focal length. The use of a star diagonal is not recommended except in the hands of an experienced observer since this reverses the field, making it extremely difficult to recognize.

CHAPTER 4

Naked-Eye Variables

Among the large number of variable stars which are known, a few never fade below naked-eye brilliance throughout the whole of their light cycle and it is to these that this chapter will be mainly devoted. Mention will also be made of the brighter novae and certain long-period variables which are brighter than sixth magnitude when at maximum.

Before going on to describe these particular stars in more detail, however, we must first examine some of the difficulties associated with the observation of variable stars by eye alone. Unlike the long-period variables which we shall discuss later, their brightness varies only by a relatively small amount. In other words, they have quite small amplitudes. This means that any personal error on the part of the observer may be an appreciable fraction of the total variations of the star itself. This is especially so in the case of those stars which are red when the Purkinje Effect is so large that it is often very difficult to draw a satisfactory light curve.

There is also the problem of finding suitable comparison stars with which to compare the brightness of the variable. Some stars such as Betelgeuse and γ Cassiopeiae which are of first or second magnitude, are far removed from other stars of a comparable brightness. In order to make a comparison, therefore, it is necessary to switch one's attention from one part of the sky to another very rapidly and this, in itself, can sometimes lead to error. One must always avoid the tendency to stare at the variable and attempt to estimate its brightness with another bright comparison star seen out of the corner of the eye.

The question of atmospheric absorption also assumes great importance here due to the inevitable large separation of the variable from the comparison stars. For this reason, such variables should be observed, if possible, when they are at their greatest altitude.

Apart from those stars which never fade below naked-eye brilliance there are, of course, many other variables which are occasionally visible without instrumental aid whenever they pass through a bright maximum. Most of these are long-period variables and although it is comparatively easy to give an approximate prediction for the date of maximum one cannot predict how bright one of these stars will be at this phase.

The long-period variable χ Cygni, for example, has a mean period of 407 days and is normally visible to the naked eye for a few weeks before and after the actual date of maximum. At its peak, it usually reaches fourth or fifth magnitude but on a few occasions it has been seen as bright as second magnitude. In a similar way, Mira can be anything between second and fifth magnitude at its brightest and on one occasion it even attained first magnitude, being comparable to Aldebaran.

Turning now to the question of the novae. Several of these which have appeared during the present century have been naked-eye objects as may be seen from Table 12. It is, of course, quite impossible to tell when a nova will appear. Statistical investigations indicate that between twenty and thirty novae appear somewhere in the heavens each year but only a comparative few attain naked-eye brilliance.

If we consider first the variables which are readily visible to the naked eye throughout the whole of their light cycles, we find that these number only a few and unfortunately all have small amplitudes, seldom exceeding one magnitude.

Betelgeuse (α Orionis), the brightest of these stars, is a red supergiant of spectral class cM2 lying at a distance of 586 light years. Its tremendous size has enabled Pease to make direct measurements of its diameter using the interferometer. The results show that this star varies in size between 300 and 400 solar diameters providing us with direct evidence that here we have a pulsating star. Betelgeuse is a semi-regular variable with a mean period of 2,070 days and varying between 0·2 and 1·3 magnitude. Throughout 1970, this variable has been around maximum brightness, between 0·3 and 0·5 magnitude and although it is difficult to be precise with stars of this particular class, minimum brightness will probably occur about November 1972.

Antares (α Scorpii) is another very bright semi-regular variable which is, unfortunately, not well placed for observers in the British Isles. Not only is it a summer star, but it never rises very high above the southern horizon. Like Betelgeuse, Antares is a red

supergiant of spectral class cM1. The mean period is 1,733 days; the visual range being 0·9 to 1·8 magnitude. At a distance of 424 light years, this star has a measured diameter 300 times greater than that of the Sun. There is also a small blue-green companion which may be glimpsed under ideal viewing conditions, especially

Table 12
THE BRIGHTER NOVAE

Nova	*Year of Outburst*	*Magnitude* Max	*Magnitude* Min
CK Vul	1670	2·7	(15·0
WY Sge	1783	5·4*	19·5
η Car	1843	−0·8	7·9
V841 Oph	1848	4·3	13·1
T CrB	1866) 1946)	2·0	10·9
Q Cyg	1876	3·0	15·2
V Per	1887	4·0*	(17·5
T Aur	1891	4·1*	15·8
V1059 Sgr	1898	4·5*	16·5
V606 Aql	1899	5·5*	(15·6
GK Per	1901	0·2	14·0
DM Gem	1903	4·8	16·5
BT Mon	1909	4·5*	16·0
OY Ara	1910	6·0*	17·5
DI Lac	1910	4·3	14·4
DN Gem	1912	3·5	14·7
V603 Aql	1918	−1·1	11·2
GI Mon	1918	5·2*	15·1
V476 Cyg	1920	2·0	15·7
RR Pic	1925	1·2*	13·6
XX Tau	1927	6·0*	(15·0
RS Oph	1933	5·3*	11·5
DQ Her	1934	1·3	15·1
V368 Aql	1936	5·0	(15·0
CP Lac	1936	2·1	15·6
V630 Sgr	1936	4·3	15·2
CP Pup	1942	0·5*	(17·0
Nova Her	1960	3·0	variable
Nova Her	1963	2·9	—
HR Del	1967	3·6	11·9

* Photographic magnitude

if an occulting bar is used to obscure the glare of the major component. At the moment, Antares is slightly below 1·0 magnitude and minimum should occur around June 1972.

γ Cassiopeiae is the brightest representative of a small group of truly irregular variables which have Be-type spectra. Unlike the two stars just described, these are extremely hot with surface temperatures in the range 12,000° to 25,000°C. Until 1929 this star appears to have been comparatively quiescent but during 1932 there were quite marked changes in its spectrum due to the development of a shell of gas around the star. About the same time, the star began to brighten slowly from its normal magnitude of 2·25, attaining 1·4 magnitude in 1937. Further shells have developed at irregular intervals since then, accompanied each time by changes in the spectrum and fluctuations in brightness. During recent years, γ Cassiopeiae has shown only small variations in brightness, varying between 2·1 and 2·4 magnitude, but continuous observation is necessary since there is no way of telling when further increases in brilliance may occur.

β Pegasi is a further naked-eye semi-regular variable with an M2-type spectrum. This star varies between 2·3 and 2·8 magnitude in a mean period of about 40 days but there are wide variations in period between individual maxima. Being a red star, one can expect quite wide differences in the estimates made by various observers. During the late spring and summer months, this variable is not easy to observe since it does not rise until early morning.

Another semi-regular variable with light changes very similar to those of Betelgeuse is α Herculis. This star was actually the first member of this class to be discovered by Sir William Herschel in 1796. α Herculis has a spectrum of type M5 and a range of 3·0 to 4·0 magnitude in an average period of 50 days, but there is some evidence of a longer, secondary period superimposed upon this primary one. Well-observed maxima of this variable were seen at the beginning of January 1970 and again in August 1970.

η Geminorum, also a red semi-regular variable, has a cM3 spectrum and an amplitude of only 0·8 magnitude, ranging from 3·1 to 3·9 magnitude. Once again, the light variations are complicated due to a long, secondary period of 2,983 days superimposed upon the primary period of 234 days. Since the Sun passes through this constellation during the summer months, this star is unobservable from the beginning of June until the middle of August.

A semi-regular star with an even smaller amplitude is ρ Persei which varies between 3·2 and 3·8 magnitude in a mean period of approximately 50 days. The spectrum is of type M4 and although a circumpolar star in North European latitudes, it lies very close to the northern horizon during the late spring and early summer when observation is further hampered by twilight.

Mention should perhaps be made at this point of α Cassiopeiae. This 2·4 magnitude star is officially classed as constant in brightness but there is some evidence of variability of the order of 0·3 magnitude and it should be closely watched for any fluctuations. The spectral type of KO is not normally found in semi-regular stars, nor even among the irregulars.

With certain of the brighter variables, more precise methods of determining their variations in brightness are required, not because their amplitudes are smaller than those just mentioned but owing to the rapidity with which their light changes. The variables so far described in this chapter all possess comparatively long periods, ranging from about 40 days to more than 8 years. As a result, their variations in brightness are relatively slow.

The problems associated with the observation of the following stars are due almost entirely to the comparative rapidity of their light variations. Quite naturally, the most accurate results are obtained by photoelectric techniques but in spite of this the difference in brightness between maximum and minimum is often sufficiently noticeable for visual estimates to be made. Unlike the long-period and semi-regular variables, the periods of these stars are generally remarkably constant although, in the case of Algol there does appear to have been a change in the period and the minima are now occurring about 0·6 hour later than predicted some years ago.

Algol (β Persei) is the prototype of a large class of eclipsing variables. Normally a star of 2·2 magnitude, it fades quite abruptly every 68 hours or so to 3·47 magnitude, the eclipse lasting 10 hours. There is a shallow secondary minimum midway between the two primary minima but this has an amplitude of only 0·06 magnitude and can only be detected by sensitive photoelectric equipment. The spectrum is of type B8 which is clearly that of the brighter companion. The spectrum of the secondary component is probably of type G4 although we are not yet absolutely certain of this.

β Lyrae is the prototype of the second major class of eclipsing variables. As will be seen from the light curve given in Chaper 2, the light variations of this star are somewhat different to those of Algol in that they are continuous, i.e. there is no relatively flat

portion when the star is at maximum brightness. This characteristic is attributed to the ellipsoidal shapes of the two components due to their close proximity. This star which has a B8 spectrum varies between 3·4 and 4·3 magnitude during the primary eclipse in a period of 12·91 days. The secondary minimum has an amplitude of 0·4 magnitude and may therefore be detected visually.

The light changes of the brightest member of the Cepheid variables, δ Cephei, may also be followed with the naked eye although the amplitude is less than 1 magnitude. This star varies between 3·7 and 4·6 magnitude in a period of 5·366 days; the spectrum changing from F5 at maximum to G2 at minimum.

There are several other bright variable stars which are readily visible to the naked eye when around maximum but since they approach the limit of naked-eye visibility when around minimum these have been included among the binocular variables in the next chapter. We must, however, examine certain of the long-period variables which come to maximum during 1971 when they should be naked-eye objects.

In searching for these particular stars, it must be borne in mind that the magnitudes given below are the brightest at which the variable has been seen, and more usually the brightness is at least a magnitude fainter than that given. When this is the case, binoculars should be used to identify the star. The position of all these variables are given in *Norton's Star Atlas*.

R Andromedae, a star with the comparatively rare Se-type spectrum, was due at maximum around 4 April 1971. The period of 408·87 days is quite long even for this class of variable. R Andromedae has been observed as bright as 5·0 magnitude but it is normally little brighter than magnitude 6·0. At minimum it can be as faint as 15·3 magnitude and a large instrument is necessary to follow it through this phase of its light cycle.

R Aquilae has a shorter mean period of 300 days, the predicted date of maximum being 5 September 1971. It has an M7e-type spectrum and can be as bright as 5·1 magnitude at maximum. Fortunately, this variable will be well placed for observation around the time of maximum. During the winter months it can only be seen close to the eastern horizon just before sunrise.

R Cassiopeiae was bright during the early part of 1971, maximum being predicted for 8 March. Although it may rise to 4·8 magnitude, normally it is only just visible to the naked eye on a clear, moonless night. The average period is 430·5 days. In North European latitudes this variable is a circumpolar star.

T Centauri lies too far south to be observable from the British Isle. The very short mean period of only 90·7 days means that this variable should come to maximum on four occasions during 1971 – 27 March, 27 June, 24 September, and 23 December. The spectrum is of Type M0e and at maximum it can be as bright as 5·2 magnitude. At minimum it rarely falls below tenth magnitude and can therefore be followed throughout the whole of its light variations with a small telescope.

T Cephei is another circumpolar variable which, on occasion, attains fifth magnitude. The mean period is one of 388·4 days and this star should be at its brightest around 10 April 1971. The spectrum is type M7e.

Mira (o Ceti) is not only one of the brightest of the long-period variables but also the one which has been most extensively observed. Indeed, it was the first variable star to be discovered and the first whose light variations were shown to be periodic in nature. As we have already seen, it can be anything between second and fifth magnitude at maximum and with a mean period of 331·5 days, the maximum is predicted for 21 June 1971 when it should be readily visible to the naked eye. Unfortunately, maximum coincides with the time when the star is at its most inaccessible, being visible low on the eastern horizon just before sunrise. With a spectrum of type M6e it may be distinguished by its red colour.

χ Cygni is another celebrated long-period variable which usually attains naked-eye brilliance at maximum. The mean period is 406·7 days and it will be at its brightest around 2 December 1971. Although it has been observed at second magnitude, such bright maxima are comparatively rare and it is usually seen between third and fourth magnitude. Care must be taken not to confuse it with 17 Cygni which lies very close to it, the two stars often being comparable in brightness when the variable is around maximum.

R Hydrae lies too far south to be easily observable from the British Isles and maximum occurred about 26 September 1970 when its close proximity to the Sun made it almost impossible to observe this phase. At its brightest it can reach 3·5 magnitude and a small telescope is sufficient to show it at minimum when it rarely fades below magnitude 10·5. The spectrum is type M7e.

R Leonis is a zodiacal variable and cannot be observed from the beginning of June to mid-August when the Sun is passing through this constellation. The present maximum predicted for 19 April 1971 and should therefore have been just observable before

the star runs into twilight. Normally, maxima are of the fifth magnitude but on occasion the variable may be as bright at 4·4 magnitude. The spectrum is type M8e and the mean period 313·1 days. It may be readily found from the sixth magnitude stars 18 and 19 Leonis.

RR Scorpii is another southern long-period variable which occasionally reaches naked-eye brilliance at maximum. The maximum occurs on August 27 1971 when the star is particularly well placed for observers in the southern hemisphere. The mean period is one of 279·5 days, the spectrum being type M6e.

Of the long-period variables just mentioned, undoubtedly the best for naked-eye observation at maximum are Mira, χ Cygni, R Hydrae, and R Leonis. Even these variables, however, are only likely to be readily visible to the naked eye when passing through exceptionally bright maxima and, of course, it is quite impossible to predict the maximum brightness of such variables from those maxima which have gone before. The naked-eye observer should therefore not be discouraged if the maxima of these stars lie below naked-eye visibility.

CHAPTER 5

Binocular Variables

The number of variable stars which may be satisfactorily observed with binoculars is naturally greater than those described in the preceding chapter. Although stars down to about sixth magnitude can be discerned with the naked eye, the problem of distinguishing one star from another becomes acute below fifth magnitude and inevitably errors are introduced when trying to make accurate estimates of brightness at the very limit of naked-eye visibility. For this reason naked-eye estimates are seldom made below fourth magnitude.

Those stars which fall within the range of binoculars include certain of the Cepheid variables, a very large number of semi-regular and irregular variables and many of the long-period variables when near, or at, maximum. Quite obviously, those variables with light cycles which can be followed completely by means of binoculars have, like the wholly naked-eye stars, only small amplitudes, usually of the order of two or three magnitudes and this introduces certain difficulties, particularly with the semi-regular stars and those which are completely irregular in their behaviour.

Most of the semi-regular variables have quite long mean periods and in many cases there is also a secondary, longer, period superimposed upon the primary cycle. One outcome of this can be that the amplitude does not remain constant but varies with the superimposed wave, usually being smaller when the star is passing through a maximum or minimum of this longer period. One variable in which this behaviour is very marked is W Cygni which has been closely observed by the V.S.S.B.A.A. and the A.A.V.S.O. for many decades. This star has an extreme range of 5·0 to 7·6 magnitude and a primary cycle of 130·6 days. For long periods, however, W Cygni shows a variation of little more than one magnitude and being a red star with an M4e-type spectrum, the Purkinje Effect and variations in colour perception among observers

often result in a scatter equal to, or greater than, the amplitude. Recent work suggests a further period of 119·8 days for this particular variable.

Many other semi-regular stars are similar in this respect adding to the difficulties in drawing reasonable light curves for them, but provided that these problems are recognized, important results may be obtained for these variables. This is particularly so when we realize that the brighter semi-regular and irregular stars have been grossly neglected until recently.

Table 13 lists several variables which fall into the category of binocular objects and the positions of all of them are given in *Norton's Star Atlas*. Charts and magnitudes for sequence stars for some of these are also given in the Appendix at the end of the book. Since any regularity in their behaviour is only approximate, no accurate dates of maxima and minima can be predicted for the large majority of these stars.

Table 13
BINOCULAR VARIABLES

Star	*Magnitude* *Max*	*Min*	*Mean Period (days)*	*Spectrum*	*Type*
V Aql	6·7	8·2	—	N	Irr
UU Aur	5·1	6·8	3400	N	SR
U Cam	7·7	8·7	411	N	SR
X Cnc	5·9	7·3	165	N	SR
W Cyg	5·0	7·6	130·6*	M4e	SR
P Cyg†	3·0	6·0	—	Bleq	Nl
U Del	5·6	7·5	—	M5	Irr
R Dor	7·1	8·1	338	M7	SR
W Gem	6·7	7·3	7·91	F6 – G5	Cep
π^1 Gru	5·8	6·4	—	S	Irr
g Her	4·6	6·0	80	M6	SR
U Hya	4·8	5·8	—	N	Irr
R Lyr	4·0	5·0	50	M5	SR
T Mon	5·8	6·8	27·02‡	F7 – K1	Cep
X Oph	5·9	9·2	335·1	M6e	LP
L2 Pup	3·4	6·2	140·5	M5e	LP
W Sgr	4·8	5·9	7·59	F2 – G6	Cep
R Scl	5·8	7·7	376·4	N	LP
R Sct	5·0	8·4	144	G0 – M5	RV
Z UMa	6·6	9·1	198§	M6e	SR

* Secondary period of 119·8 days
† A nova-like variable which rose to third magnitude in 1600 A.D.
‡ Variable period
§ Secondary period of 1560 days

Of the variables given in Table 13, one is perhaps worthy of further mention here. P Cygni is the type star of a small number of variables sometimes known as the permanent novae. In 1600 it rose to third magnitude where it remained until 1606 when it commenced fading slowly and became invisible to the naked eye by 1626. In 1654 the star brightened again to just above naked-eye visibility and following a period of numerous minor fluctuations reached fifth magnitude in 1715 where it has remained ever since. Although the variations in brightness are quite small, rarely exceeding 0·2 magnitude, it is quite possible that P Cygni may repeat its earlier performance.

The most noteworthy characteristic of P Cygni and other variables of this type lies not in their light changes, but in their spectra. These exhibit a few bright emission lines with absorption components on their violet borders. From the underlying absorption spectrum we can say that these variables are fairly typical O or B type stars. The fact that the absorption components are shifted towards the violet indicates that they originate in a huge diffuse shell of gas around the star and come from that part of this extended atmosphere lying between us and the star. The corresponding emission lines originate from the atmosphere on either side of the star, namely that portion through which the underlying continuum does not pass. There is now little doubt that the P Cygni variables consist of hot, intrinsically bright stars, possibly supergiants, which are continuously ejecting mass into the surrounding gaseous envelope.

Long-Period Variables in 1971

A large number of the long-period variables reach maximum during 1971 when they are readily visible with binoculars. Obviously, it is impossible to list all of these and Table 14 lists only a few of the brighter long-period stars. For completeness, some southern variables are also given.

When searching for these variables with binoculars, it must be borne in mind that as with all stars of this type, maximum may occur any time within three or four weeks before or after the predicted date. In general, the variable may be distinguished from the surrounding stars by virtue of its reddish colour.

Table 14

Star	Magnitude Max	Magnitude Min	Period (days)	Spectrum	Predicted date of maximum
R And	5·0	15·3	409	Se	Apr 5
R Aql	5·1	12·0	300	M7e	Oct 6
R Ari	7·2	13·7	187	M3e	July 5
R Aur	6·6	13·8	458	M7e	Dec 6
S CMi	6·9	13·4	333	M7e	Sep 16
R Cas	4·8	13·6	431	M7e	Apr 9
R Cyg	5·9	14·6	425	Se	Aug 20
R Gem	5·9	14·1	370	Se	May 26
V Mon	6·0	14·0	334	M5e	Oct 4
T Nor	6·5	12·7	243	M4e	(Jan 28 (Sep 28
U Ori	5·2	12·9	373	M8e	July 25
R Psc	7·0	14·8	344	M4e	June 11
R Sgr	6·6	13·3	269	M5e	Sep 17
RR Sco	5·0	12·2	279	M6e	Aug 29
R Ser	5·6	14·0	357	M7e	Oct 22
R Tel	7·8	15·2	461	M6e	Nov 29
R Tri	5·4	12·0	266	M4e	Aug 29
R UMa	6·2	13·6	301	M4e	May 9
S Vir	6·0	13·0	377	M7e	Dec 5
R Vul	7·0	13·6	137	M4e	(May 6 (Oct 1

Four other variables, not included among the types just mentioned, may be mentioned here; two R Coronae Borealis stars and two of the recurrent novae.

R Coronae Borealis, the type star of this small group of very important variables, lies just at the limit of naked-eye visibility when at maximum but accurate estimates of brightness require binoculars. The behaviour of these stars is, as we have seen, completely unpredictable. Following a prolonged and complex series of light variations which began in June 1962, R Coronae Borealis returned to normal maximum during the latter half of 1969 and has remained around sixth magnitude with only small fluctuations ever since. The variable is readily found from the chart given in the Appendix and its position is also marked in *Norton's Star Atlas*.

Although seldom rising above 5·8 magnitude, there appear to have been several short, sharp peaks in the light curve during 1970 with the star seen as bright as 5·6 magnitude while at other times

it has been as faint as 6·4 magnitude. Whether this behaviour is the prelude to a further fading is a matter of conjecture but undoubtedly the variable should be closely observed for the first indications of any steep drop in brightness. A rather complex series of changes take place in the spectra of these variables during the initial decline, and if these are to be observed as completely as possible it is essential that the professional observers should be notified immediately a decline is suspected.

If the star should fall below 6·5 magnitude it may be assumed that a decline has set in although it is, of course, quite impossible to predict how faint the star will become before the inevitable climb back to normal brightness. On several occasions, subsidiary minima have been observed with the star fading only to around seventh magnitude and these may be followed completely with binoculars. At times of a deep minimum, with the star fading to about fourteenth magnitude, large apertures are necessary to define the light curve.

The second R Coronae Borealis variable which is an easy object for binoculars at maximum is RY Sagittarii. This star unfortunately lies too far south for satisfactory observation from North European latitudes but it has been comprehensively studied by observers in the southern hemisphere. The range of 6·0 to 14·0 magnitude is almost identical with that of R Coronae Borealis and in general their light variations are very similar. Both are highly luminous supergiant stars of spectral type GOep showing an abnormal abundance of carbon in their atmospheres and a pronounced deficiency of hydrogen.

T Coronae Borealis has been mentioned earlier in Chapter Two and is the brightest of the recurrent novae at maximum. It must be admitted that the two outbursts of this star which have been observed, in 1866 and 1946, were separated by 80 years and the star is at present quite invisible with binoculars, varying slightly between 9·8 and 10·2 magnitude in an irregular manner. However, it is worth while to examine the position of this star, which lies in the same binocular field as R Coronae Borealis, on every possible night since there is no way of telling when its previous performance may be repeated. The light curve of this star during the two previous outbursts is given in Fig. 37.

The field of RS Ophiuchi should also be examined whenever possible particularly as the period between outbursts of this star is much shorter than that of T Coronae Borealis. This recurrent nova has erupted in 1901, 1933, 1958, and 1967, and although the

maxima have been unequal in brightness it can attain 5·8 magnitude at its brightest, well within reach of binoculars.

PROBLEMS ENCOUNTERED IN BINOCULAR OBSERVATION

Apart from the necessity of providing a firm support for binoculars to ensure steadiness of the star images, there are certain other problems associated with binocular observing of variable stars of which the observer should be aware in order that his estimates are as accurate as possible. This applies in particular to observations of the semi-regular and irregular variables which have comparatively small amplitudes.

The difficulty of finding bright comparison stars close to the variable is obviously not as acute as in the case of the naked-eye stars but nevertheless it can, at times, present a very real problem. Owing to the relatively wide field of view, the major problem often resolves itself into one of unconsciously observing the variable in the centre of the field by direct vision with a comparison star some distance away by averted vision. For accurate results it is essential to bring both stars into the centre of the field as quickly as possible. This will also help to minimize position angle error which can otherwise lead to quite large inaccuracies in one's estimates.

Since the majority of variable stars suitable for observation with binoculars are semi-regular or irregular variables, together with long-period variables around maximum, the Purkinje Effect can play a dominant role in increasing the scatter among observers, since all of these are red stars. In all probability, this will be most marked in the case of the long-period variables where binocular estimates are combined with those made telescopically owing to the difference in apertures.

The wide field produced by binoculars may also introduce errors due to atmospheric absorption owing to a wider separation of the brighter comparison stars from the variable. The much smaller field of the average telescope, coupled with the larger number of fainter comparison stars available comparatively close to the variable, tends to reduce this effect.

CHAPTER 6

Telescopic Variables

In the last two chapters we have become acquainted with those variable stars which may be followed through at least part of their light variations with the naked eye and binoculars. As would be expected, the number of variables within reach of binoculars is far greater than those which can be seen merely with the naked eye. The use of a telescope greatly increases the number which can be observed. With a 6-inch or 8½-in reflector which are fast becoming the most popular sizes of instrument for amateur work, the number runs into many thousands, far more than can possibly be observed by any one observer. Here then, it is worth making the point that it is far better to observe a few stars thoroughly than to make sporadic observations of a large number.

The long-period variables offer a rich field of work for the possessor of a small telescope since the minima of several of these stars are within reach of such an instrument. A 3-inch refractor, for example, will show stars down to 11·5 magnitude under good seeing conditions when there is neither moon nor twilight. Certain of the brighter U Geminorum variables may also be observed, at least through the brighter portion of their light cycles with small or moderate apertures.

Some variables, of course, require large apertures for satisfactory results to be obtained. The large majority of the dwarf novae are extremely faint objects, even at maximum, seldom being brighter than 13·0 magnitude while at minimum they require instruments larger than 12 inches in diameter to be seen at all. The R Coronae Borealis variables, although some are visible in binoculars and small telescopes when at maximum, often fade below fourteenth magnitude during their deep minima and are then beyond the reach of anything smaller than an 8-inch telescope.

Almost inevitably, it becomes progressively more difficult positively to identify the variable in the field of a large instrument when the star is very faint. Not only is the field of view much

smaller than in binoculars or small telescopes, but the number of faint stars in the vicinity of the variable is far greater and very often one is working close to the limiting magnitude of the telescope. Identification can be particularly difficult when averted vision has to be employed in order to see the star or when the variable lies in one of the rich star fields of the Milky Way.

When observing telescopic variables it is very desirable to know the scale of the chart being used and also the field of view for each eyepiece used since a great deal of time can be wasted when trying to identify groups of stars as shown in the charts with those seen through the telescope.

As the observer becomes more proficient in variable-star observing, it is only natural that he will wish to undertake work on as many different types of variables as possible. Here the question of the limiting magnitude of the telescope can be of paramount importance in determining those types which can be satisfactorily observed and those which cannot. When a star is passing through a particularly faint phase of its light cycle and is therefore invisible in the observer's instrument, the importance of negative observations must not be under-estimated. Nevertheless, such observations are far from satisfying from the standpoint of the observer and for this reason it may be more satisfactory for the observer to undertake work only on those variables which he is able to follow throughout the whole of their light cycles with the instruments at his disposal.

A small, or moderate-sized telescope is sufficient for the study of the brighter long-period variables and a large number of semi-regular, nebular, and Cepheid variables, and certain of the flare stars. Such an instrument, however, would be almost useless for observing the large majority of the U Geminorum and Z Camelopardalis variables. It is therefore important that in the observation of telescopic variables the observer should be aware of the limitations of his instrument.

Telescopes Between 3 and 5 inches Aperture

The approximate limiting magnitudes for telescopes of this size range vary from 11·7 magnitude for a 3-inch refractor to 13·0 magnitude for a 5-inch instrument. Apart from a host of short-period variables such as the RR Lyrae and eclipsing stars which are not particularly suitable for amateur observation except with specialized equipment, there are many others which can be followed completely with instruments in this range of apertures. These include long-period variables, semi-regular variables, the brighter nebular variables and certain of the flare stars. A small number of the dwarf novae also lie within reach of such instruments.

Since it is quite impossible to discuss all variables under these headings which are observable with small instruments, we shall confine ourselves to a relatively small number of each class.

(a) **Cepheid variables.** Although the Cepheids as a class are not the most suitable type of variable to observe, particularly in view of their comparatively small amplitudes, certain of the longer period representatives can prove interesting objects for a small telescope. Their long periods, too, mean that inevitable gaps in the light curve do not assume the same importance as for those stars with shorter periods and since any variations from one cycle to another are usually extremely small, the results obtained from several cycles may be superimposed to provide quite a satisfactory light curve.

Charts for the stars listed in Table 15 are given in the *Atlas Stellarum Variabilium* and that for TX Cygni, a typical member of this group, is given in the Appendix.

Table 15

Star	*Magnitude* *Max*	*Min*	*Period (days)*	*Spectrum*
U Car	6·1	7·6	38·75	F9 – K3
SZ Cyg	8·9	9·7	15·11	F8 – G8
TX Cyg	9·6	12·0	14·71	F5 – G6
X Pup	8·2	10·0	25·97	F2 – K2
Z Sct	9·8	11·2	12·90	G0 – M0
W Vir	9·7	11·0	17·27	cG0p

(b) **Semi-regular variables.** Some of these stars have already been discussed in the previous chapter and their general behaviour is outlined in Chapter 2. The semi-regular stars have unfortunately been neglected during much of this century and very useful information may be obtained from a continued study of their light fluctuations. In particular, the values given for their mean periods, especially those of any secondary periods which may be superimposed upon the primary cycle still require further substantiation. As many of these secondary periods are several years in length, such observations must naturally be continued over a long period.

Indeed, this appears to be the main reason why we still lack reasonably accurate values for them.

For this reason, the periods for the variables given in Table 16 must be regarded as being very approximate. The double period of V Lyncis provides quite a complex light curve for this star. S Persei has been comprehensively observed for many years and the existence of two periods is fairly well established. The longer period has a suspected amplitude of 2·8 magnitudes but many more observations are needed before a full statistical analysis can be carried out to unravel the complexities of the light curve. A chart for this variable is given in the Appendix together with a magnitude sequence.

Table 16

Star	*Magnitude Max*	*Min*	*Period (days)*	*Spectrum*
RR Cam	9·6	11·3	124	M6
S Cen	8·1	10·0	65	N
RU Cep	8·5	9·4	109	M0
RU Cyg	6·9	10·2	461	M8e
V Lyn	8·6	9 8	54 and 87	M5
S Per	7·2	12·2	810 and 916	cM3e
T Psc	9·3	12·3	258	M5
W Tau	8·5	13·0	265	M5

(c) **Long-period variables.** The predicted dates of maxima of certain long-period variables in 1971 have already been given in the two previous chapters and here we shall confine ourselves to a discussion of these stars when around minimum brightness. As will be readily appreciated, the maxima are usually well covered by means of binoculars and quite often there is a surfeit of observations available during this phase of the light cycle. Many more observations are, however, urgently needed for these stars at minimum and even a small telescope may be used to great advantage in obtaining such estimates.

As in the case of the maxima, the predicted dates of minimum must be regarded as only approximate. Many of these variables have comparatively flat minima during which the brightness of the star varies only slightly for quite a long period.

Table 17

Star	*Magnitude Max*	*Min*	*Period (days)*	*Spectrum*	*Predicted date of minimum*
R Aql	5·1	12·0	300	M7e	June 1
R Boo	5·9	13·1	223	M4e	April 23
V Boo	6·4	11·5	258	M3e	March 27
R Cnc	6·1	11·9	361	M7e	July 15
T Cas	6·7	12·7	445	M8e	Sept 10
o Cet	2·0	10·1	331	M6e	March 20
U Cyg	6·1	12·2	462	Ne	June 5
S Del	8·2	12·7	277	M6e	May 22
R Leo	4 4	11·6	313	M8e	Oct 17
W Lyr	7·2	13·1	196	M4e	March 3 Aug 15
U Ori	5·2	12·9	373	M8e	March 5
S Pyx	8·3	13·1	207	M3e	Feb 11
S UMa	7·1	12·9	226	Se	July 13
S UMi	7·5	13·0	324	M7e	July 2
S Vir	6·0	13·0	377	M7e	June 21

(d) **Nebular variables.** A large number of these irregular variables lie within reach of a small telescope and since their light fluctuations can be quite rapid it is essential that they should be observed on every possible night. As we saw in Chapter 2, they may be conveniently divided into three main groups, namely the RW Aurigae, T Orionis and T Tauri variables depending upon their spectra and the nature of their light curves. Inevitably, of course, there is often a good deal of overlap among these groups, especially when they are so faint that satisfactory spectra cannot be obtained.

Since all are associated with either dark or bright nebulae they tend to aggregate in certain fairly well-defined regions, notably in the Orion Nebula and in the neighbouring constellations of Auriga, Monoceros, Carina, and Corona Australis. Being totally irregular it is, of course, quite impossible to predict their behaviour and for this reason alone they will repay continuous study. Normally, the amplitudes are relatively small and there are often long periods when the variable remains almost constant in brightness.

Charts and sequences are given for two of the brighter nebular variables in the Appendix. T Orionis has an extreme range of 9·5 to 12·1 magnitude and has an AO type spectrum. Like many of these variables it is embedded in the bright nebula. The other

variable, T Tauri, is associated with Hind's variable nebula NGC 1555. This small patch of nebulosity was readily visible in small instruments when discovered in 1852 but nine years later it had faded appreciably and was completely invisible by 1868. Since that time, marked changes in luminosity have been observed and although it is clearly visible in large telescopes at the present time, it appears that the shape has altered considerably. T Tauri itself has an extreme range of 9·5 to 13·0 magnitude but for long periods it varies by only half a magnitude or so, the light curve often giving the impression of sinusoidal waves.

(e) **Flare stars.** Although the total number of flare stars known is comparatively small, this is due more to their intrinsic faintness than to a real deficiency within the galaxy.

When observing flare stars it must be remembered that their light variations are so different from those of most other variables that a special observing technique is necessary if satisfactory results are to be obtained. Since a flare generally lasts for only a matter of minutes, observations must be made at regular intervals, preferably every five minutes or so, for long periods. Not only are flares relatively infrequent but the really spectacular ones during which the star may brighten by up to six magnitudes are rarer still. In order to fit flare stars into the observing programme it is perhaps best to return to the star between observations of the other variables on the programme. Such a procedure may also tend to minimize any errors due to bias.

The chart and sequence for EV Lacertae, a typical flare star, is given in the Appendix. This particular star has a very close, twelfth-magnitude companion, not shown on the chart since it requires a fairly large aperture to divide these two stars and except when this is possible it is best to treat this close double as a single star and use their combined magnitude as a standard.

Telescopes Between 6 and 12 inches Aperture

Telescopes with apertures within this range have limiting magnitudes from about 13·5 to 15·0. Consequently, the number and types of variables which may be observed are increased enormously. As we have already seen, best results on variable stars are obtained when the star examined is not more than about three magnitudes brighter than the limiting magnitude of the instrument. When a star is particularly bright, therefore, a large telescope should be stopped down or a smaller instrument used.

Large telescopes in this aperture range are consequently used to their best advantage in following stars when they are faint. The brighter variables (and the brighter phases of the long-period variables) are usually adequately observed by smaller telescopes and it is when a variable is fainter than about thirteenth magnitude that estimates are urgently needed.

For this reason, we shall only discuss those observations which may be made with advantage by such instruments. There are, for example, several long-period variables which, although they have been continuously observed for many decades have poorly defined light curves at minimum due to a paucity of observations during this phase. A similar state of affairs exists for R Coronae Borealis, RY Sagittarii, and SU Tauri whenever these R Coronae Borealis variables pass through a deep minimum.

A large instrument also brings within easy reach many of the dwarf novae and irregular variables. These particular stars are becoming increasingly important in many fields of astronomical research and a plea for amateur observers having moderately large telescopes at their disposal to extend their observations to include more of these variables on their programme was recently made by Commission 27 of the I.A.U.

Table 18

Star	*Magnitude* *Max*	*Min*	*Period (days)*	*Spectrum*	*Predicted date of minimum*
R And	5·0	15·3	409	Se	Dec 25
R Cam	6·8	14·4	271	Se	July 20
Z Car	9·6	15·1	383	M6e	Aug 27
S Cas	6·2	15·3	612	Se	June 3
R Com	7·3	14·6	362	M5e	July 29
R Cyg	5·9	14·6	425	Se	Apr 4
χ Cyg	2·2	14·3	407	Mpe	July 1
R Gem	5·9	14·1	370	Se	Jan 15
R Lyn	6·5	14·8	379	Se	Aug 31
RY Oph	7·2	14·4	151	M5e	May 7 Oct 5
R Per	7·7	14·7	210	M3e	May 2 Nov 28
S Sgr	9·1	15·0	231	M4e	Apr 12 Nov 29
R Ser	5·6	14·0	357	M7e	June 2
R Tuc	8·7	15·2	286	M5e	Apr 27
T Vir	8·2	14·8	339	M6e	Aug 5

(a) **Long-period variables:** The long-period variables given in Table 18 are all grossly under-observed at minimum and all positive estimates made when they are around minimum brightness are of particular importance.

(b) **R Coronae Borealis variables:** Very few of these stars are known at the present time and since they are among the intrinsically brightest stars it appears unlikely that many more will be discovered in the near future although it would clearly be unwise to be dogmatic on this point in view of the comparatively recent discovery of XX Camelopardalis which, with a photographic range of 8·7 to 10·3 magnitude is among the brightest of this small class of variable.

In Chapter 9 we saw how these stars spend most of their time around maximum brightness, fading irregularly and unpredictably, often by as much as 8 magnitudes. Details of most of the members of this class have been given in Chapter 2 and a chart and sequence for R Coronae Borealis are given in the Appendix.

(c) **U Geminorum and Z Camelopardalis variables:** Although the light curves for several of these variables are reasonably complete over the last half century or so, it is only comparatively recently that any substantial insight has been gained into the physical nature of these stars and there is still a large number within range of a 12-inch telescope which have either been only spasmodically observed or not observed at all since their discovery. Indeed, for many we do not even know such a fundamental parameter as the period!

Almost all of these stars exhibit a phenomenon known as 'flickering' when at minimum brightness with the light varying rapidly and apparently irregularly by about half a magnitude or so. Observations at minimum are also highly desirable in that they may show evidence of eclipse. The eclipse of U Geminorum, for example, has an amplitude of more than half a magnitude and should be well within the detection of a 12-inch instrument.

In recent years the major amateur organizations have begun a comprehensive observing programme to cover all of these stars in both hemispheres which attain 13·5 magnitude or brighter at maximum and it is anticipated that this will soon provide valuable information on the behaviour of these variables. Charts and sequences for three dwarf novae—RX Andromedae (a Z Camelopardalis variable), SS Cygni and X Leonis (U Geminorum variables) are given in the Appendix.

TELESCOPES LARGER THAN 12 INCHES APERTURE

Although the number of instruments of this size in amateur hands is still comparatively small, some observers either possess such telescopes or have access to them. Such instruments are most useful for very specialized work in the field of variable-star observation. Assuming that the observer is equipped purely for visual observation, there are a number of stars which need particular attention including some long-period variables which fade beyond the limit of the instruments we have just discussed and the fainter dwarf novae. Several of the old novae should also be observed occasionally since there is evidence that even many years after the star has returned to its former brightness, irregular fluctuations continue to occur. Nova GK Persei (1901), for example, still exhibits flare-like eruptions with an amplitude of two magnitudes and several other members of this class are irregularly variable to a certain extent. Many of these stars are now extremely faint objects and beyond the reach of most instruments in amateur hands.

(a) **Long-period variables.** One or two of these which have been observed for many years often fade below sixteenth magnitude and very few estimates are available to define satisfactorily the light curve. Such stars as those given in Table 19 are therefore ideally suited for study.

Table 19

Star	*Magnitude* *Max*	*Min*	*Period (days)*	*Spectrum*	*Predicted date of minimum*
V Cam	8·0	16·2	519	M7e	July 20
U Cas	7·6	16·0	278	Se	Aug 28
X Cep	8·7	17·2	534	M6e	June 21, 1972
S Cyg	8·8	16·8	323	Se	Apr 18
V Del	8·1	17·3	536	M6e	Jan 29, 1972
R Her	7·3	15·8	322	M6e	July 19
W Lib	10·3	16·0	204	M7e	May 15
RX Lyr	10·8	16·0	250	Me	Dec 5 Apr 4 Nov 10
Z Sgr	8·1	15·9	450	M5e	Dec 12
RV Vir	10·0	15·9	269	M5e	May 13

(b) **U Geminorum and Z Camelopardalis variables.** The work already outlined in the preceding section may be extended even further with the use of a larger instrument. Of the dwarf novae which have been observed for some considerable time, two are extremely faint at minimum. UV Persei is characterized by short, abrupt increases in brightness from a minimum of about 16·8 magnitude and although the mean period is undoubtedly long for a star of this type it is quite evident from the results so far obtained that some revision of the presently accepted value of about 200 days will be necessary.

SW Ursae Majoris is very similar in its behaviour, often fading to 16·4 magnitude at minimum. The mean period is even longer than that of UV Persei although in this case too, more observations will inevitably result in a drastic revision as many of the short maxima must have been missed owing to adverse weather conditions. A recent spectacular maximum of this variable was observed during February 1970 when it rose to 9·8 magnitude and remained bright for a month before fading below thirteenth magnitude. Such behaviour is very reminiscent of the well-known 'super-maxima' of SU Ursae Majoris.

In summary, we may conveniently divide the observational work on telescopic variables into three sections depending upon the aperture of the instrument and from what has been said it is clear that a very wide selection of variable stars may be studied with the larger telescopes being employed mainly for specialized work on the fainter stars.

CHAPTER 7

The Light Curve

We must now consider in more detail the end product of our observations of variable stars, observations which may be visual, photographic, photovisual, photometric, or photoelectric. This is the light curve of the variable which is simply the curve we obtain when we plot the brightness of the star against time. If sufficient observations are available, this will generally tell us by inspection, the class of variable to which a particular star belongs.

X, Y Coordinates

The **x-coordinate** of the light curve universally denotes time in some form or other depending usually upon the period and type of the variable. For the short-period stars such as the eclipsing variables, both of the Algol and β Lyrae types, and the RR Lyrae and short-period Cepheids, the x-coordinate is usually divided into units denoting tenths of the phase (see Fig. 5). For the eclipsing variables the primary minima are located at phase 0·0 and 1·0. The zero point for the RR Lyrae and Cepheid variables is normally maximum brightness.

When we come to consider those stars having longer periods, the long-period, semi-regular, irregular, R Coronae Borealis, and U Geminorum variables, together with the novae, we may use either the ordinary calendar date or the Julian Date, the latter being more usual for scientific purposes. In these cases, the phase cannot be used satisfactorily since the individual maxima and minima vary so much from one cycle to the next (in the case of the short-period stars just mentioned, each cycle is essentially identical).

Where the calendar date is concerned, no further mention is necessary but it will be worth while here to say a little more about the Julian Date. The Julian Period is used by astronomers to calculate the exact interval between dates at long periods apart and began at noon on 1 January, 4713 B.C. The Julian Date (abbreviated

J.D.) is therefore the number of days which have elapsed since the beginning of the Julian Period. To simplify mathematical calculations, decimals of a day are used instead of hours and minutes.

As the Julian Date begins at noon and not midnight, G.M.A.T. is used for recording times of observations and not U.T. This has the additional advantage that there is no necessity to change the date in the middle of the observing period. Thus 1 January, 1971, 3 a.m. U.T. is J.D. 2,440,952·125 (Julian Period 1970, 31 December, 15 hours).

The y-coordinate gives a measure of the brightness of the variable and except in the case of photoelectric observations is in magnitudes, either visual, photographic, photovisual, or photometric. Photoelectric measurements are made by means of a photoelectric cell and provide results which are highly accurate, giving the difference in brightness between two stars. The photoelectric cell is extremely useful for detecting small and rapid variations in variable stars, the variable being compared with a comparison star which has a spectral type as close as possible to that of the variable. Since such cells differ in their sensitivity to the various colours there is no photoelectric magnitude scale and in this case the y-coordinate gives the magnitude difference between the comparison star and the variable.

Calculation of Dates of Maxima and Minima

Although it is usually a comparatively simple matter to determine the class of variable from the general shape of the light curve, more often than not it can be quite difficult to make an accurate determination of the date of maximum or minimum. This is due solely to the fact that in the majority of cases the light curve is far from symmetrical. This asymmetry is particularly noticeable for the Cepheids, long-period, semi-regular, and U Geminorum stars. When we consider the irregulars, of course, no trace of symmetry exists at all.

The most useful method, that of bisected chords, was developed by Pogson (Fig. 43). As may be seen from Fig. 43 it is far easier to determine the dates on which a variable attains the same magnitude on both the ascending and descending branches of the light curve and by bisecting the lines joining these points and drawing a smooth curve through these midpoints, we thereby take into account the marked asymmetry of the light curve.

Drawing the Light Curve

Let us see now how a satisfactory light curve may be drawn from the observations. An observer working alone may, of course, draw a light curve from the observations made over a period and thus obtain some idea of how a star has behaved. Inevitably, there will be gaps in such a curve due to a variety of circumstances, not the least of which will be adverse weather conditions which can, at times, prevent any observations being made for considerable periods.

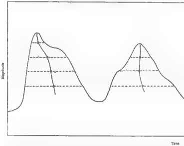


Fig. 43. *Determination of dates of maximum and minimum by Pogson's method of bisected chords*

Quite obviously, the most accurate light curve will be that derived from observations made by a large number of observers. In this way, the perversities of the weather are minimized and if the observers are widely scattered geographically, the number of gaps can be drastically reduced or perhaps eliminated entirely.

Basically, there are two methods of drawing a light curve from the observations made by several observers. In the first, all of the estimates may be plotted and a mean curve drawn through all of the points. This method has the advantage that it shows at once the scatter of the observations about the mean curve.

Secondly, the observations for each day are averaged and only the mean values plotted, the weight given to each value being determined by the number of individual observations which contributed to it. Where numerous observations are concerned, this has the advantage of reducing the number of points which have to be plotted. A modification of this method which may be employed for those stars whose brightness varies relatively slowly, for example the long-period variables, is to average the observations over five or ten days, thereby obtaining the five- or ten-day means. This naturally reduces the number of points to be plotted still further. It does have the disadvantage, however, that in certain cases it may smooth out short-term fluctuations which might otherwise be shown on the light curve.

Bright and Faint Observers

If different symbols are allotted to the various observers contributing to a light curve, an analysis will often show that certain observers tend to estimate red stars brighter than the average while others see them fainter. This effect has already been discussed in detail in Chapter 3 and is due to variations in the colour perception among observers.

On this basis, the compiler of the light curve may sometimes be able to apply a correction, either positive or negative, to make allowance for this. It must be emphasized, however, that this can only be done when the observer either over-estimates or under-estimates the brightness of the variable by a consistent amount. Errors can easily be introduced by universal use of such magnitude corrections.

An examination of results obtained for a large number of long-period variables over several decades has shown that there have been many instances where such a procedure can be dangerous. Two experienced observers may be a 'faint' and 'bright' observer of red stars when the variable is at minimum brightness but when at maximum, their colour perceptions are reversed, the 'bright' observer estimating the variable fainter than the other throughout this phase. It would therefore seem that a great deal more research must be done on colour perception, and possibly also on the way in which the colour of these stars changes throughout the light cycle, before such corrections can be universally applied.

Interpolation and Extrapolation

Very often there are appreciable and unavoidable gaps in the light curve due to a variety of causes. Chiefly these are caused by adverse weather conditions, periods when the star is visible only during the later hours of the morning and lack of suitable instruments if the variable is particularly faint. In the case of the zodiacal variables, of course, gaps are inevitable when the sun is passing through that particular constellation.

When the gap occurs on either the ascending or descending branch of the light curve and both maximum and minimum are reasonably well defined, it is possible to interpolate in order to join the gap. On the other hand, when either maximum or minimum has not been covered by observation, extrapolation may be attempted although this usually yields more inaccurate results. In either case, the fact that the results have been interpolated or extrapolated must be made clear. In the case of the long-period, semi-regular, and irregular variables, it must always be borne in mind that interpolation is hazardous and extrapolation is to be avoided if at all possible. It is in this respect that negative observations, especially of the irregulars such as the U Geminorum and Z Camelopardalis variables, are so important. Since the maxima of these stars can be very short, sometimes lasting only a day or two, a good series of negative observations is often sufficient to tell whether or not a maximum has been missed due to adverse weather conditions.

Standard Deviations

We have already seen that owing to the personal equation of different observers there is inevitably a scatter of estimates about the mean light curve. This scatter is usually small for white or yellow variables such as the eclipsing stars, Cepheids, dwarf novae, novae, and the R Coronae Borealis stars when at maximum. In the case of red variables, the long-period variables for example, this small scatter cannot be hoped for owing to the widely varying sensitivity of the human eye to red and the Purkinje Effect.

Estimates differing by half a magnitude or so are to be expected even when similar instruments and magnifying power are used. When results obtained with large apertures are combined with those obtained with smaller instruments then a scatter of up to two magnitudes may often be found. When this is the case, clearly the technique is wrong and this serves to underline the undesirability of using large apertures when red stars are bright.

In view of this, it is useful to have some means of measuring the dispersion of the individual observations about the mean value statistically and the best, and most accurate, method of doing this is to derive the standard deviation.

If $X_1, X_2, X_3, X_4 \ldots X_n$ are n values of a set, then the arithmetic mean is given simply by

$$M = \Sigma X / n \tag{1}$$

From this we see that each value of X lies at some specific distance from the mean M, this being known as the deviation for that value. In other words, if x is the deviation (which may be either positive or negative), then

$$x = X - M \tag{2}$$

The standard deviation (σ) is then defined as

$$\sigma = \sqrt{\Sigma x^2 / n} \tag{3}$$

Let us take an example to see how this works in practice. We will suppose that five observers have made the following estimates of a variable star on the same night: 8·1, 8·3, 8·4, 8·5, and 8·7 magnitude. We now wish to determine the standard deviation from these observations. The arithmetic mean of these values is given by

$$M = \Sigma X / n = 42{\cdot}0 / 5 = 8{\cdot}4$$

By subtracting the individual estimates from this value we obtain the following deviations

$$-0{\cdot}3, \quad -0{\cdot}1, \quad 0, \quad +0{\cdot}1, \quad +0{\cdot}3$$

The sum of the squares of these deviations is therefore

$$(-0{\cdot}3)^2 + (-0{\cdot}1)^2 + 0^2 + (0{\cdot}1)^2 + (0{\cdot}3)^2 =$$

$$0{\cdot}09 + 0{\cdot}01 + 0 + 0{\cdot}01 + 0{\cdot}09 = 0{\cdot}2$$

From this we obtain the standard deviation

$$\sigma = \sqrt{0{\cdot}2/5} = \sqrt{0{\cdot}04} = 0{\cdot}2$$

As might be expected, for a given number of observations, the standard deviation is smaller for white or yellow variables than for red ones such as the long-period stars. The real value of the standard deviation is that it enables us to determine whether any small change in brightness is real or simply due to random scatter. If the variation in magnitude is larger than the standard deviation then we are justified in assuming the change to be real. This is especially helpful when examining the light curves of the dwarf novae at minimum for evidence of eclipse since here we have the added information that the variation due to eclipse will be repeated at regular intervals and will show up quite readily in the light curve.

CHAPTER 8

Charts and Sequences

The lunar and planetary observers have the advantage over workers in the field of variable-star observation in that the objects they study are readily picked out against the stellar background. In the case of any kind of stellar work, charts are necessary in order to identify the particular star one is observing. Very early in the history of variable-star research it became necessary to draw charts of the various star fields and also to make up sequences of stellar magnitudes for the comparison stars which are used to estimate the brightness of the variable.

Early Star Atlases and Catalogues

Very simple lists of bright stars date back to the time of the Babylonians, being used mainly for religious ceremonies. The first scientific attempt to catalogue the stars was made by Hipparchus about 127 B.C. but unfortunately no surviving record of this remains and the earliest extant catalogue is that drawn up by Ptolemy about A.D. 137 and known as the Almagest. This gives the positions and approximate magnitudes of 1,028 stars.

With the advance of astronomy, and especially following the invention of the telescope which revealed many thousands of fainter stars, the need for more complete catalogues – and also more accurate ones – became increasingly urgent. Throughout the eighteenth and nineteenth centuries this work engaged the attention of several astronomers and among the more impressive of the catalogues brought out during this period may be mentioned: the catalogue of 10,000 southern stars compiled by Lacaille in 1763, Lalande's catalogue of 1801 giving the positions of more than 47,000 stars, and finally the Bonner Durchmusterung prepared by Argelander and his colleagues and published between 1859 and 1862. This great work lists the positions and magnitudes of 324,198 stars in the northern hemisphere down to Declination –23°. Two further supplements were added later, one listing 133,659 stars south

of Declination –24° and the Cordoba Durchmüsterung containing 579,000 stars lying still further south.

All of these atlases were produced by normal visual observation but with the advent of celestial photography, far more accurate and comprehensive charts are now available. The Carte du Ciel with a limiting photographic magnitude of 14 is intended to cover the entire sky but is, as yet, incomplete. When published, it is estimated that the positions of some 10,000,000 stars will be accurately charted. The Palomar Sky Survey charts cover the area from the North Pole to Declination –27° and are taken in red light (with a limiting magnitude of 20) and in blue light (limiting magnitude 21). The recently issued Vehrenberg Atlas has a limiting photographic magnitude of 13.

Of more importance to variable-star observers are the charts given in the *Atlas Stellarum Variabilium* by Fr. Hagen which have a limiting visual magnitude of 14 and are specifically designed for variable-star observation. Further volumes of this Atlas and Catalogue are issued at irregular intervals.

Variable-Star Charts

The early charts issued by the V.S.S.B.A.A. were based mainly upon the Bonner Durchmusterung for the 9° and 3° charts and upon the charts given in the *Atlas Stellarum Variabilium* for the 1° and 20′ charts. It was soon recognized that the magnitudes given in the B.D. were in error, particularly at the faint end of the range and even those given in the catalogues for the *Atlas Stellarum Variabilium* were not sufficiently accurate below about ninth magnitude.

More recently, the charts have been based upon those issued by the A.A.V.S.O. and the magnitudes of the fainter comparison stars determined visually at the Leander McCormick Observatory. The latest charts for faint U Geminorum and Z Camelopardalis variables are taken from photovisual photographs, the magnitudes of the comparison stars being measured directly by means of a microdensitometer.

The scale of the V.S.S. charts has remained virtually unchanged for more than half a century. The 9° field chart gives the position of the variable relative to several naked-eye stars and in certain cases, where the variable is particularly bright at maximum (e.g. o Ceti and χ Cygni), these are also used as comparison stars. The 3° field chart includes some of the nearer stars given on the 9° chart and also brings in fainter stars close to the variable. In a

similar manner, the 1° and 20′ charts, as well as introducing fainter comparison stars and defining the position of the variable more exactly, each contain a number of stars given on the preceding chart. The observer is thus able to proceed stepwise from one chart to the next, going up or down the series as the variable brightens and fades.

A few variables which are either particularly bright or faint require additional charts. For example, a 30° chart is necessary for o Ceti in order to include very bright comparison stars for use when this variable is passing through a bright maximum. At the other end of the scale, some variables are so faint that 10′ and 5′ charts are required. The latter charts are, of course, needed only by those observers having large instruments at their disposal.

The scales used by the A.A.V.S.O. on their charts are a little different to those just mentioned, although the principle is the same. In general, five chart scales are used as follows:

Scale a: 5′ = 1 mm
Scale b: 60″ = 1 mm
Scale c: 40″ = 1 mm
Scale d: 20″ = 1 mm
Scale e: 10″ = 1 mm

Choice of Comparison Stars

The prime requisite of a comparison star is, of course, that it must not be variable. Unfortunately, where faint stars are concerned, this is not always apparent at the time they are chosen and it is only after they have been used for a period that any irregularities which may be present in their brightness, are noticed. Several new variable stars have indeed been discovered in this way. A further requirement is that that comparison star should be reasonably close to the variable so that both may be brought rapidly into the centre of the field of view without too much movement of the telescope. This is not too difficult to achieve where faint comparison stars are concerned but with the brighter ones in the sequence, this is not always possible.

The large majority of the comparison stars used are either white or yellow stars and we have already seen that in the case of the long-period and semi-regular variables we are thus forced to compare a red variable with a white or yellow comparison star, thereby introducing the Purkinje Effect. The ideal situation of comparing such variables with stars of a similar colour cannot,

unfortunately, be realized. Not only are there insufficient red stars to be used as comparisons, but most, if not all, red stars are variable to a certain extent.

A further ideal which cannot always be realized, is to choose a sequence of comparison stars so that the interval between any two in the sequence does not exceed 0·5 magnitude. Inevitably, there are cases where suitable comparison stars cannot be found in the field of the variable, resulting in larger gaps which simply have to be tolerated.

Determination of Comparison Star Magnitudes

In order to obtain satisfactory light curves for variable stars it is, of course, necessary to have accurate measurements of the magnitudes of the comparison stars used in the sequences. In the early days of variable star observation, considerable confusion arose due to each observer making up his own sequence and employing his own determinations of comparison-star magnitudes. In many instances where the same star was used as a comparison, the magnitude assigned to it varied considerably among observers. This unsatisfactory state of affairs persisted throughout most of the last century even though the need for some standard procedure was recognized by many astronomers.

The situation was eased somewhat with the formation of the large amateur organizations for observing variable stars when determined efforts were made to adopt standard sequences.

The Revised Harvard Photometry

Most of the early magnitudes were based on the Bonner Durchmusterung catalogue. Many of these values, however, are seriously in error particularly at the faint end of the range below seventh magnitude. During the years 1897 to 1906, more accurate determinations were made at the Harvard University College using the 2-inch and 4-inch meridian photometers with Polaris as the standard. We now know that Polaris is variable with an amplitude of 0·14 magnitude, a fact which was not known at the time of the original determinations. The 4-inch meridian photometer was also used at Arequipa in Peru for similar determinations to be made on stars in the southern hemisphere and in 1908, the results were published in *Harvard Annals* Nos. 50 and 54.

The former lists the photometric magnitudes of 9,110 stars in both the northern and southern hemispheres brighter than 6·5 magnitude. The latter gives similar determinations for 36,682 stars

fainter than 6·5 magnitude, the limiting magnitude for the series being 10·5.

The magnitudes given in the Harvard Revised Photometry were adopted and used for many years until they were superseded some thirty years later by photovisual determinations made at several observatories.

For comparison stars fainter than 10·5 magnitude, various other sources have been used from time to time. Notably among these are those made by Hagen for his *Atlas Stellarum Variabilium* which were determined specifically for stars in variable-star fields and consequently cover only small, selected areas of the sky. Even here, many of the earlier values were subsequently found to be in error and more accurate determinations were made at the Leander McCormick Observatory.

Once a sequence of visual magnitudes for comparison stars is set up, only minor modifications are usually necessary. Such changes are due mainly to the fact that the photovisual magnitudes do not always correspond exactly to those determined by the average eye and changes are occasionally made to compensate for this.

The addition of new variables to the observing programme has meant the drawing of charts and the setting up of sequences to cover these. Since few charts are available for these stars and many are extremely faint at minimum, photovisual photographs are being used increasingly for this purpose.

Two methods of designating the comparison stars on the charts are in use by the V.S.S.B.A.A. and the A.A.V.S.O. The former allocate letters or numbers to the stars on the charts and issue a separate sequence of magnitudes, while the latter simply give the adopted magnitude on the chart to the first decimal place with the decimal point omitted to avoid confusion.

CHAPTER 9

Photographic and Photoelectric Observations

So far in this book we have concentrated mainly on visual observation of variable stars. There are several reasons why this is so. When the large amateur organizations such as the V.S.S.B.A.A. and the A.A.V.S.O. were formed at the end of the last century, few of their members possessed the equipment necessary for astrophotography or photoelectric work and the types of stars chosen for communal observation were those best suited for visual observation.

The long-period, semi-regular, and R Coronae Borealis variables, together with the novae and dwarf novae are still generally observed by ordinary eye estimates without the aid of photometric or photographic instrumentation. In view of the large amplitudes of these variables and the nature of their light changes, the accuracy obtainable by purely visual methods is quite sufficient for good light curves to be drawn. In addition, although a single photograph will provide a permanent record of several hundred stars, the long exposures and accurate driving of the telescope necessary mean that in the time taken for a single plate to be exposed and developed, thirty or forty visual estimates may be made.

It must not be imagined, however, that photography has no role to play in variable-star observation. Most of the new discoveries in this branch of stellar astronomy are made by photography. For example, the photographic surveys of selected star fields in the Milky Way have resulted in the finding of many hundreds of faint variables Other advantages which photography possesses over visual methods are the cumulative nature of the process making visible stars which are far too faint to be observed visually, the fact that hundreds of stars are recorded simultaneously and that, being a permanent record, the photograph may be examined at any convenient time. In particular it enables very accurate comparisons to be made from a series of plates taken over a long period. The camera, too, is quite objective in what it records unlike the eye which is

strongly subject to personal error. The old saying that the camera does not lie, however, does not strictly apply to astrophotography.

From the very early days of stellar photography, it was recognized that the picture obtained of the stars by photography is not the same as that which the eye sees. The early photographic emulsions were relatively more sensitive to blue light than to red compared with the eye which has its maximum sensitivity in the yellow.

As a result, blue stars appear brighter photographically and red stars fainter than their visual magnitudes. The difference between the photographic and the visual (or more accurately the photovisual) magnitude of a star is known as the colour index. On the Harvard colour index scale, a star of spectral type AO has a colour index of zero (the photographic and photovisual magnitudes are the same). Blue stars have negative colour indices whereas yellow and red stars have positive ones. Colour indices in excess of two magnitudes are seldom encountered. On the negative side, stars of Type O have colour indices of about −0·4 magnitude, while on the positive side, the N-type stars have colour indices of about +5·5 magnitudes.

One method of minimizing the effect of colour index is to use special isochromatic plates or films and a suitable yellow filter, this combination producing results which are very close to visual estimates. Such photovisual magnitudes are becoming increasingly important and more and more amateurs are now equipping themselves to take stellar photographs using such films and filters. Very valuable work can be done in the variable-star field by using HP4 film and a Wratten 8 yellow filter which give results very close to photovisual magnitudes. Such a filter is both inexpensive and readily obtainable but for more accurate work one of the somewhat more expensive isochromatic filters is useful. The disadvantage of the Wratten 8 and similar filters is that they pass a fairly broad region of the visible spectrum whereas the isochromatic filters allow only a narrow band in certain colours to pass.

Focal Plane Photography

In essence there are two basic methods of determining magnitudes by photography. The first depends upon the fact, discovered by Bond in 1857, that the size of the photographic image is related to the brightness of the star and the length of the exposure. This is known as focal plane photography, the plate (or film) being placed at the focus of the telescope. The stars will then appear

as points of light which, except in the case of the very bright stars, should appear perfectly round providing that the driving mechanism of the telescope is sufficiently accurate. The brighter stars often appear cruciform in outline, this being an optical effect which is difficult to eliminate.

Focal plane photography is still the only method for photographing very faint objects. To determine the magnitudes of the stars on the plate, the negative is usually placed on the stage of a low-power microscope and a standard series of images, prepared by increasing the exposure in a geometrical ratio, is inserted into the same field. Measuring the brightness of a star is then quite a simple procedure. The star in question is placed between two adjacent images on the graduated scale such that one is slightly brighter and the other slightly fainter than the star. By interpolation, it is possible to obtain an accuracy of about 0·5 magnitude by this method.

There are unfortunately certain corrections which have to be applied for the greatest accuracy, some of which can be quite complex. These depend upon the distance of the star from the centre of the field and also upon the colour of the star.

Extrafocal Photography

The method of focal plane photography is undeniably rapid and, as we have seen, the only method available for very faint stars. Apart from the corrections mentioned above, however, there are other factors which contribute to certain inaccuracies, factors which are difficult, if not impossible, to eliminate. The light-sensitive silver grains in the emulsion, for example, are not distributed as evenly as one would wish and on development of the negative there are inevitable irregularities associated with these small grains which, since the images themselves are usually extremely small, can introduce marked errors into the determinations. There are also local defects in the emulsion introduced during manufacture of the plates which are difficult to detect before exposure and which can have an analogous effect. Finally, the diameters of the images show only a slow increase as a function of magnitude.

To get over these difficulties, Janssen suggested a modification of the above method which is, however, applicable only to the brighter stars. Here the plate is placed slightly in front of or behind the focal plane of the telescope. Instead of point images, therefore, the stars will now appear as round discs which are sufficiently large for any irregularities due to the distribution of the silver grains to be negligible.

The intensity of the image on the negative is now a function of the magnitude and at the same time that the exposure is made, a series of images of known relative brightness formed by a calibrated optical wedge is recorded. Determination of brightnesses is then made by the same method as before, comparing the degree of darkening of the extrafocal images with the standards.

In order to facilitate such measurements and also to improve accuracy, a microphotometer is often employed. One of the first of these instruments was devised by Hartmann in 1899 in which the extrafocal image and that of an optical wedge are projected side by side in the eyepiece, illuminated by a split beam from a small bulb. Adjustment of the wedge is then made until the two halves of the field are equal in brightness. Unfortunately, this instrument possesses one serious drawback. The eyepiece magnifies the silver grains in the emulsion of the extrafocal image and this granular appearance is sufficiently different from the uniformly illuminated optical wedge to make accurate comparison difficult.

This is overcome by a development due to Fabry and Buisson in which the ocular of the eyepiece is removed. This results in the two halves appearing evenly illuminated and determinations accurate to about 0·03 magnitude may be obtained by this method.

Telescopes for Photographic Work

Not all telescopes are equally suited for photographic work. In order to give good results, the telescope should have a low *f*-number. This is given by the focal length of the objective divided by the aperture. Telescopes with large *f*-numbers are said to be 'slow' which means that to produce satisfactory images either the star must be bright or the exposure relatively long.

The large reflectors used mainly for photography have ratios of *f*/5 or less. The 200-inch Hale reflector at Mount Palomar, for example, has a ratio of *f*/3·3 and the Schmidt telescopes which are used exclusively for stellar photography are even 'faster'. Indeed, some small Schmidt telescopes have recently been constructed in which the *f*-number is less than unity.

Photography in Variable-Star Work

There are several fields in which photography can prove extremely useful in variable-star work. We shall now examine each of these in detail.

Many variable stars are extremely faint when at minimum brightness and can be followed visually through this phase only by the use of very large instruments. The big advantage of the photographic plate is, as we have already seen, that it accumulates the light which falls upon it. The eye, of course, does not do this. If a star is too faint to make an immediate impression upon the retina, continued staring will have no effect. The photographic emulsion, however, will continue to be affected by the small amount of light it receives, gradually building up an image throughout the exposure.

For a given aperture, therefore, a long-exposure photograph will show images of stars much too faint to be seen with the eye. This at once suggests the usefulness of photography for following such stars through their faint minima when visual methods cannot be used. If possible, an orthochromatic or panchromatic film should be used with the appropriate yellow filter so that the results obtained are, as near as practical, on the photovisual scale. Such estimates may then be compared directly with visual observations made throughout the remainder of the light cycle. If such filters and films are not available, ordinary photographic magnitudes may be derived and a suitable correction applied depending upon the spectral type of the variable and the comparison stars which are used to determine the photographic magnitude.

A further important contribution comes simply from making a collection of photographs of certain regions of the sky and especially those bordering the Milky Way. Although several of the brighter novae are discovered visually, information concerning the pre-nova stage is of vital importance. Such photographs often yield unexpected dividends. One recent example of such work carried out by an amateur is that of the photograph taken of the Serpens region in 1968 by W. E. Pennell which shows the pre-nova stage of Nova Serpentis (1970) as a faint star of 13·6 magnitude. Many other cases are known in which old photographs have provided a wealth of detail concerning the pre-outburst histories of novae. As always, of course, it is essential to note the date and time of the exposure as well as its length and the conditions of development of the negative since these obviously have an important bearing on any information subsequently derived from them.

Finally, of course, photography has proved of invaluable use in the discovery of new variable stars. Since this aspect will be discussed in detail in Chapter 11, very little will be said about it at this point. Here it will be sufficient to say that careful comparison

of photographs taken under similar conditions will often reveal stars which have changed in brightness over the intervening period and by checking the position of the star with those listed in the *General Catalogue of Variable Stars* one may determine whether the variable is new or one which has previously been observed.

Three-Colour Photometry

As we have just seen, photographic and photovisual magnitudes differ according to the colour of a star. The colour index therefore represents a measure of the blueness or the redness of a star. In order to standardize conditions so that results obtained at different observatories may be compared not only are the emulsions used prepared by the same technique but also the wavelengths at which the observations are made. In two-colour photometry, the wavelengths are about 5,000 Å (using a yellow filter) and about 4,300 Å (using a violet filter). This naturally yields more precise values than the less accurate method of comparing visual and ordinary photographic magnitudes.

In three-colour photometry, an additional determination of brightness is made in the ultra-violet region of the spectrum using special emulsions and filters. This is generally known as the U, B, V system of photometry. In its application to variable stars it provides light curves showing the variation in brightness of the star at each of these three wavelengths. For those stars which have only small amplitudes, a photoelectric cell is used in conjunction with the telescope.

The light curves normally obtained by this method of photometry correspond to V, B – V and U – B. The first is the photovisual curve which is very similar to that obtained visually. The second provides us with a measure of the excess blueness of the star throughout the light cycle while the third gives an indication of the ultra-violet flux. Such light curves provide essential information concerning the physical processes going on within the star as the visual brightness varies.

More recently, this technique has been extended to cover a wider range of wavelengths which allows the energy distribution of a star to be plotted as a function of the wavelength. The curves we obtain from six-colour photometry are not only characteristic of the spectral type but also tell us whether the star is a giant or dwarf. For example, we find that for a giant and a dwarf star of the same spectral class, the giant is richer in the infra-red and the dwarf relatively richer in the ultra-violet.

Photoelectric Observations of Variable Stars

By using the techniques just described, photographic magnitudes may be determined with an accuracy about 20 times greater than purely visual estimates, even this accuracy is surpassed, however, by means of a photoelectric cell which is based upon the photoelectric effect discovered in 1888.

When light falls upon the surface of a thin film of certain metals such as caesium and potassium, electrons are emitted provided that the wavelength of the light is sufficiently short. In the photoelectric cell these electrons are collected on a wire or metal grid which acts as the anode, the whole arrangement being enclosed in an evacuated chamber. Usually a potential difference of about 100 volts is applied across the anode and cathode to facilitate the passage of these electrons.

The small current produced by these emitted electrons was originally measured with an electrometer but as this is a very delicate device and not particularly suited to being mounted on a telescope it was soon replaced by a galvanometer. More recently, the accuracy of the photoelectric cell has been dramatically increased by the use of a device known as a photomultiplier tube which amplifies the current more than a million times by means of a series of charged plates in the tube.

Within certain limits, the photoelectric current is directly proportional to the intensity of the illumination unlike the darkening of a photographic plate which depends upon a series of complex factors that are not always easy to evaluate. The great advantage of the photoelectric cell, however, is the rapidity with which measurements can be made. The effect is immediate compared with the several hours which are often required for one photographic exposure. We do, however, lose the cumulative effect of the photographic plate and are therefore limited to those stars which are sufficiently bright to have an instantaneous effect upon the cell.

At the present time the photoelectric cell has been used mainly for accurate photometric determinations of magnitudes from photographic negatives, in the form of a refined densitometer, and for precise estimates of the magnitudes of bright stars, in particular of rapid and small changes in the brightness of variables.

There are a few classes of variable star which have extremely small amplitudes. The β Canis Majoris variables, for example, have amplitudes rarely exceeding 0·1 magnitude and it is quite obvious that these cannot be followed either visually or photo-

metrically. β Canis Majoris itself varies between 2·02 and 2·08 magnitude in a period of 0.250031 days and other members of this class have even smaller ranges of brightness. Although only a few members of this class are known at present it appears almost certain that this is because only the brighter representatives have been discovered photoelectrically and undoubtedly large numbers exist throughout the galaxy.

The magnetic variables, too, have similar amplitudes and their light variations can only be followed by means of photoelectric equipment. The main interest of these particular stars lies in the fact that these stars all have strong magnetic fields which also vary semi-periodically. Some astronomers are of the opinion that the magnetic field is responsible in some way for the apparent stability of the variations in brightness but so far no direct correlation between the two parameters has yet been found. For example, the star with the strongest magnetic field so far measured has only a small variation in brightness and any correlation between the changes in the field and the corresponding light fluctuations is extremely tenuous. The whole question of the origin of these magnetic fields is engaging the attention of astronomers at the present time, particularly since there is some evidence that every rotating body of stellar dimensions will produce a magnetic field.

One further class of variable for which photoelectric observations have yielded vital information are the dwarf novae. Most observers are familiar with the typical major outbursts of these stars but what is not so well known is that most, if not all, of these stars are, like the old novae, binary systems. This fact was first revealed by their spectra and led to a search for eclipsing systems among these variables. Unfortunately we encounter two problems where the dwarf novae are concerned. Firstly, only 200 or so of these variables are known and the fact that the planes of their orbits are randomly aligned in space immediately reduces the number in which eclipses will occur. Secondly, and equally important, by far the greater number of these stars are faint objects even when at maximum brightness.

One further difficulty is that the best opportunity for observing an eclipse is during minimum phase when determinations are uncomplicated by additional factors arising during a major outburst. All of these stars exhibit minor fluctuations in brightness when at maximum which can confuse the observations.

U Geminorum itself, however, is an eclipsing system and sensitive photoelectric determinations in three colours by Krzeminski have provided vital information regarding the nature of the outbursts of this variable. The amplitude of the eclipse in this case is approximately one magnitude and should, therefore, be observable visually.

Photoelectric Determinations

We have already seen how the emulsions and filters used in photographic work have been standardized by international agreement so that direct comparison may be made between observations made at different observatories. Photoelectric cells, on the other hand, differ appreciably in their sensitivities and it is not possible to set up a photoelectric standard. The method of making photoelectric determinations of magnitude is therefore a little different to that of photographic estimation of brightness.

Here a companion star of similar magnitude and spectral type and which is constant in brightness is chosen close to the variable and three readings made; the comparison star, the variable, and finally the comparison star again. Since the magnitude of the comparison star is constant there is no need to convert the brightness of the variable into magnitudes. More usually the photoelectric light curve is simply a plot of the difference in magnitude between the two stars against time.

CHAPTER 10

Spectroscopic Observation

In the previous chapters we have been mainly concerned with the light variations of variable stars. The reason for this, of course, is that the majority of amateur variable-star observers do not possess the instrumentation necessary for recording stellar spectra. In the various tables given in Chapter 2, however, the spectra of several stars have been given and mention has also been made of certain spectroscopic changes which take place throughout the light cycles of these stars, changes which yield vital information about the physical and chemical processes which bring about stellar variability. In order to understand more fully what these imply it is appropriate here to go into the subject of stellar spectroscopy a little more thoroughly.

The value of spectroscopy as applied to astronomy cannot be over-estimated. In 1825, for example, the French philosopher Comte stated quite emphatically that although much could be discovered concerning the mechanics of the stars – how they move through space and their distributions within the galaxy – it was quite impossible for astronomers ever to determine anything at all about their chemical and physical constitution. Thanks to the spectroscope and the discovery of the laws governing atomic and molecular radiation, we now know a very great deal about the composition of the stars and the physical and chemical processes going on in their interiors. When used in conjunction with the light variations of the eclipsing binaries, the spectroscopic observations provide us with a wealth of data concerning the masses, surface temperatures, diameters, densities and orbital elements of the component stars. The problems associated with the outbursts of the novae, supernovae, U Geminorum, and flare stars are being solved with the help of the spectroscope. The pulsation theory of the RR Lyrae stars, Cepheids, and long-period variables has received added confirmation from direct spectroscopic measurements. From all of

this, it is apparent that our knowledge of these stars would not have progressed to the point it has without such observations.

General Principles of Spectroscopic Analysis

Spectroscopic analysis really began with the classic experiments carried out by Newton as long ago as 1666. By passing a ray of sunlight through a glass prism, he was able to show that it is broken down into a band of colours which he termed the solar spectrum. He was further able to demonstrate – by passing the light of the individual colours through a second prism – that these could not be decomposed further. They are therefore known as the primary colours.

Much later, in 1800, William Herschel found that when a thermometer with a blackened bulb is moved along the solar spectrum, a heating effect is observed which extends beyond the red end of the visible spectrum. These invisible radiations he named the infra-red spectrum. The following year, Ritter demonstrated that similar invisible radiations lie beyond the violet end of the spectrum which are capable of effecting chemical reactions. For example, they affect a photographic plate in much the same way as visible light. This part of the spectrum is known as the ultra-violet.

At first it was considered that the infra-red, visible, and ultra-violet regions represented distinct types of radiation but this view has been discarded by modern physicists. All are of the same fundamental kind belonging to what is known as the electro-magnetic spectrum. The different properties they possess are due simply to the wavelength of the radiation. Indeed, the human eye is a very poor receptor of radiation, being sensitive only to an extremely narrow band of wavelengths.

The wavelengths are usually expressed either in Angstroms (1 Å = 0.0000001 mm.) or in microns (1 = 0.001 mm.). The visible spectrum extends from about 4,000 Å at the violet end to 7,500 Å at the red end. The ultra-violet may be examined by means of ordinary photographic plates up to around 2,000 Å and still further with special techniques to about 150 Å. The infra-red is traceable to about 12,000 Å (1·2 microns) by using special photographic emulsions and out to the limit of the solar spectrum, 50,000 Å (5·0 microns) by other methods.

Both ultra-violet and infra-red radiation is absorbed by our own atmosphere and if we wish to examine these regions satisfactorily we are forced to make observations, of the Sun or the stars, from high-altitude balloons or better still, from orbiting satellites.

For more than a century since Newton's original experiments the solar spectrum was thought to be continuous. That is, that it consists only of the band of colours, each blending imperceptibly into the other. It remained for Wollaston, in 1802, to show that when the sunlight is passed through a narrow slit and not a circular hole, the spectrum thus obtained contains a number of dark lines. At the time it was believed that these dark lines were merely boundaries between one colour and the next, particularly since five of these lines do indeed seem to divide two colours quite neatly. This idea persisted until Fraunhöfer made the first detailed examination of the solar spectrum in 1815. By using a grating in place of a prism and a small telescope to view the spectrum, he discovered several hundred dark, narrow lines which are known as the Fraunhöfer lines.

Over the course of the next fifty years or so, the spectroscope was modified until it assumed its present form in 1832 when Babinet replaced the simple slit by a collimator in which the slit is mounted in the focal plane of the objective. Eleven years later, Draper constructed the first spectrograph in which the solar spectrum is produced on a photographic plate. In 1872, Draper also obtained the first stellar spectrogram, that of Vega, which showed four of the dark lines of hydrogen.

During this time too, chemists and physicists were obtaining large numbers of spectra under laboratory conditions and the outcome of this work was the recognition of three fundamental types of spectra.

1. The continuous spectrum. When a solid is heated to incandescence, we obtain what is known as a continuous spectrum. This is merely the featureless band of colours which Newton obtained and in which no dark or bright lines are present. Liquids also give a continuous spectrum as do gases provided that they are subjected to sufficiently high pressures as in the deeper levels of a star.

2. The emission spectrum. Here the background, or continuum, is dark, the spectrum consisting of a series of bright, coloured lines, the colours corresponding to that part of the spectrum in which they appear. This is the type of spectrum produced by an incandescent gas under low pressure when there is no other medium lying between the source and the spectroscope. Typical sources of emission spectra are glow discharge tubes such as neon and mercury vapour lamps and the Sun's corona.

3. The absorption spectrum. This is the kind of spectrum which is characteristic of the Sun and the majority of stars. Here the background continuum is crossed either by dark lines (due to atoms) or dark, broad bands (due to certain molecules). Only gases and vapours produce absorption spectra. The conditions for producing an absorption spectrum are that we must have an incandescent source enveloped by an absorbing gas usually at a lower temperature and pressure than the incandescent source itself. In the Sun and many stars we have the photosphere which is the incandescent source surrounded by the outer atmosphere.

Although the above differences between the three types of spectra was recognized by the first half of the nineteenth century, it was not until 1862 that Bunsen and Kirchhoff brought some order out of the confusion which still existed by establishing the following 'laws' of spectroscopic analysis:

(a) every chemical element or compound produces its own specific spectrum which may be used to identify it, and

(b) every such element or substance can absorb the same wavelengths of radiation as those which it emits.

Once these fundamental principles were recognized, it was then possible not only to identify the lines due to the various chemical elements and molecules but also to explain the reason for the absorption spectra found in so many of the stars, including the Sun. When the light from the deeper levels of a star passes through the cooler, and less dense, atmosphere, the atmospheric gases absorb certain of the wavelengths corresponding to those which they would emit if they, themselves, were the source of the radiation. The particular region within a stellar atmosphere in which this occurs is known as the reversing layer since it is here that this reversal of emission to absorption lines takes place.

Once the camera was combined with the spectroscope, the science of stellar spectroscopy made rapid advances beinning with Draper's classic spectrogram of Vega taken in 1872 to the tremendous programme of classifying stellar spectra initiated by Pickering in 1882 and culminating thirty-six years later in the publication of the *Henry Draper Catalogue* which lists the spectra of some 225,000 stars. It is upon this publication that the Harvard sequence of stellar spectra is based; a sequence which, with some modifications, is now universally used by astronomers.

The Diffraction Grating

Before we go on to consider the Harvard sequence in some detail, however, mention must first be made of a second way by which spectra may be obtained other than by use of a prism. This is by means of a diffraction grating. The first gratings were constructed by winding thin metal wire over the threads of a narrow pitch screw. More recently, a method has been developed for engraving fine parallel lines on either glass or metal plates using a diamond tip. These lines are all equally spaced and when a beam of light falls obliquely upon such a grating, it is split into a series of diffraction spectra which are said to be of first, second, third order, and so on.

A diffraction grating has the disadvantage that the available light is divided among the various spectral orders whereas a prism concentrates all of the light (apart from a little which it absorbs) into a single spectrum. It is possible, however, with modern techniques to produce gratings in which more than 90 per cent of the light goes into a spectrum of the first order. The great advantage of the grating, on the other hand, is that it spreads out all of the wavelengths to the same extent whereas a prismatic spectrum is dispersed more at the blue end than the red.

The Harvard Sequence of Stellar Spectra

About 1866, Secchi made the first attempt to classify the stars according to their spectra. The relatively small number of spectra he had at his disposal enabled him to define three main types arranged in order of decreasing temperature. Type I are white stars, the spectra consisting predominantly of hydrogen lines. Type II are yellow stars with prominent lines due to metals in the spectrum, and Type III are red stars which show dark, broad bands due to certain molecules (mainly titanium and zirconium oxides). This rather simple scheme was further modified by Vogel in 1874 but apart from its historical significance, this sequence is now little used by astronomers.

By the end of the last century, progress in stellar spectroscopy had developed to such an extent that it was soon recognized that Secchi's system was no longer sufficiently accurate or comprehensive. With the need for a much more detailed system, that developed by the investigators at the Harvard College Observatory soon became universally adopted. Like that originated by Secchi, the system is one based upon decreasing surface temperature, the types being initially arranged in alphabetical order. As further data accumulated, certain

types were omitted and others added until the present series is: O, B, A, F, G, K, M, R, N, and S. Three further classes are occasionally used for special purposes, these being Type W for the Wolf-Rayet stars, closely associated with Type O; Type P employed for gaseous nebulae, consisting of bright emission lines of hydrogen together with those of oxygen and nitrogen which have had several of their orbital electrons removed by the peculiar physical conditions prevalent in these nebulae, and Type Q which is used for the novae.

The sequence is a continuous one with the various spectral characteristics changing smoothly from one type to the next. As a result, each type is subdivided further into ten sub-types. For Type O these are lettered from 'a' to 'e' and then by a number from 1 to 5. Types B to M are subdivided by a number from 0 to 9. At the lower end of the sequence, Type S is not subdivided into any subgroups, while Type N is divided only into N1 to N3.

The major characteristics of each type of spectrum are as follows:

Type O. Owing to the high temperatures prevailing in these stars, the lines found are those due to ionised atoms (those in which one or more of the outer electrons have been stripped off owing to the very high temperatures of 30,000° to 40,000°C.). Helium is the element which gives rise to the strongest lines and for this reason they are commonly known as the ionised helium stars. Lines of doubly and trebly ionised oxygen and nitrogen are also present. As stated earlier, those stars with spectra of sub-types Oa, Ob and Oc have now been placed in a separate category, type W (the Wolf-Rayet stars). Very few stars with this type of spectrum are known.

Type B. The temperatures of these stars, in the region of 12,000° to 25,000°C. are not sufficiently high to ionise helium and the predominant lines are due to this element in its neutral state. Ionised oxygen and nitrogen still produce lines, however, but the strength of all of these lines decreases gradually throughout this type while at the same time, hydrogen lines begin to make their appearance, sometimes seen as bright emission lines against the background continuum. We now know that this latter feature is indicative of the presence of a huge, tenous atmosphere surrounding the star. The presence in the spectrum of these bright emission lines is indicated by the suffix 'e' and the irregular variable γ Cassiopeiae is typical of this small group.

Although there does appear to be a large number of stars known with B-type spectra, this is mainly due to their very high luminosities which enables us to see them over great distances. There also seems to be a tendency for them to aggregate in clusters and since one of the best known of these lies in the constellation of Orion, they are sometimes known as Orion stars.

Type A. Stars having A-type spectra are very numerous due both to their high intrinsic brightnesses and also to their real abundance in space. The lines due to hydrogen are at their greatest intensity between types A0 and A1 becoming gradually weaker thereafter. The surface temperature is now between 8,000° and 12,000°C. resulting in the virtual absence of helium lines and the appearance of those due to ionised metals, particularly calcium.

Type F. In the early subdivisions of this type the lines of hydrogen and ionised calcium (the latter showing in the ultra-violet) are of almost equal intensity. As we progress from F0 to F9, lines due to the former element decrease in strength while those of the latter increase. At the same time there is a steady development of fine absorption lines due to various metals, these reaching their maximum intensity in the succeeding type G. The surface temperatures of these stars are between 6,000° and 8,000°C.

Type G. These are the so-called Solar stars since the Sun itself is of spectral type dG2. The main characteristics are the gradual weakening of the hydrogen lines and the development of numerous lines due to metals of which the best represented is iron. The surface temperatures lying between 4,000° and 6,000°C., are too low to produce any significant ionisation of atoms.

It is among the Type G stars that we find a very important distinction, one which begins to show in stars of the preceding type and which becomes increasingly important in those which follow. Detailed examination of this class of spectrum has shown that in some the majority of the absorption lines are much finer than in others and the relative intensities of certain lines are quite different. We now know that these differences in the two kinds of G-type spectra are due to pressure. The spectra containing very narrow lines (a function of low pressure) are those of giant stars, the other type with broader lines (due to a higher pressure) are those given by dwarf stars. To distinguish between giants and dwarfs of the same spectral type, the prefixes 'g' and 'd' are used. Capella, for example, is a spectroscopic binary consisting of two giant stars of spectra types gG8 and gG0 while the Sun is a dwarf star of spectral type dG2.

Type K. Lines due to metals, particularly iron, are always present and very intense in these spectra while the lines due to ionised calcium reach their maximum at type K1. The surface temperatures of K-type giants lie in the range 3,500° to 4,500°C.; those of the dwarfs between 4,000° and 5,000°C. At the lower ends of these temperature ranges, certain molecules are formed and the spectra of the later subtypes show a banded appearance due to these molecules, notably titanium oxide.

Type M. Almost all of these are variable to a certain extent. The spectra are dominated by fluted bands due to titanium oxide, the bands fading towards the red side. The surface temperatures of these stars are very low, between 2,000° and 3,500°C. and again we find both giant and dwarf stars included in this type. Very numerous lines due to neutral metals are present while those of hydrogen are almost invisible except in some of the long-period variables when they appear in emission at certain phases of their light variations.

Type S. Again, virtually all of these stars are variable and their spectra closely resemble those of type M except that the fluted bands are due to zirconium oxide. The surface temperatures too are very like those of stars of the preceding type. From the evidence we have at the moment, it would appear that all of the S-type stars are giants.

Type N. Like the two preceding types, the spectra of these stars which are all giants are dominated by fluted bands. Here, however, the bands fade towards the violet side and are due to carbon compounds rather like those found in comets. Most, if not all, of the N-type stars are variable.

Type R. This is a comparatively rare type of spectrum and previous to 1908 such stars were included in Type N. Visually, it is difficult to differentiate between the two but photographically, the blue and violet regions of the spectrum are brighter than Type N. Such stars are not as red as those of Types M or N. It is not easy to determine the surface temperatures of the N- and R-type stars but they would appear to range from 2,000° to 3,000° C.

When we come to examine the various types of variable stars we find that although they include the entire range of spectral types, it is possible to assign the various types among the different classes of variable. Type O spectra are found almost exclusively among the T Orionis variables and certain of the eclipsing stars. Other early-type spectra, B, A, and F are found among the Algol and β Lyrae variables and also the RR Lyrae stars.

The Cepheids, in general, tend to have later-type spectra, varying between F and G as do the RV Tauri stars. G-type spectra also preponderate among RW Aurigae variables and flare stars. The long-period and semi-regular variables belong almost entirely to spectral types M, N, and S while the R Coronae Borealis stars show a marked preference for spectra of type R.

Spectrographs

To obtain stellar spectra, the astronomer has three basic types of spectrograph at his disposal, each used for a specific purpose. As one might expect the vast programme of stellar spectroscopy initiated by Pickering in 1882 could never have been undertaken using an ordinary spectroscope providing the spectrum of one star at a time. Some modification is obviously necessary to allow the spectra of many stars to be photographed at the same time on a single photographic plate.

In order to do this, Pickering used an objective prism first described by Secchi. Since the stars are so distant from us we may regard them as being at infinity and consequently the rays of light we receive from them are virtually parallel. As a result we do not require a collimator to bring them to a focus upon a photographic plate. All that is necessary is to place a large prism having a small apex angle in front of the telescope objective. So long as there is sufficient light to register on the plate, low-dispersion spectra may be recorded of all the stars in the field.

We must remember, of course, that ordinarily the spectrum of a star obtained under these conditions will be a very fine line revealing no detail at all. Some method must clearly be used to widen it in order to identify any salient details. The method used by Pickering was to align the objective prism so that its edges were horizontal when the telescope was on the meridian. The spectra therefore extended north and south on the plate. By adjusting the clockwork-driving mechanism so as to gain or lose a few seconds per hour, the spectra were then widened sufficiently for the lines to be observed.

The objective prism therefore lends itself to the large-scale survey of stellar spectra and from this to statistical work.

The slit spectrograph (Fig. 44) uses a collimator to render the rays of light from the telescope (which are focused on the slit in the collimator) parallel. The light then passes through a prism and into a photographic chamber where wide-dispersion spectra are formed on the photographic plate. This type of spectrograph is used to study single, relatively bright objects and has the advantage that the spectrum is spread out to a large extent revealing very fine detail.

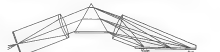


Fig. 44. *The slit spectrograph*

When we wish to examine the spectra of faint objects, a slitless spectrograph is employed and although the spectra thus obtained are only of low or medium dispersion they do, nevertheless, allow us to gain some information concerning stars which are beyond the reach of either the objective prism or the slit spectrograph.

The Laws of Atomic and Molecular Radiation

Earlier in the present chapter we saw that while the astronomers were applying empirical spectroscopic analysis to the spectra produced by stars, the physicists were attempting to determine why the various atoms and molecules give rise to the numerous lines found in spectra. This was necessary in order to identify many of the narrow lines found either in emission or absorption in stellar spectra including that of the Sun.

The first general rule to be recognized was that the discrete, narrow spectral lines are produced by atoms whereas molecules give rise to bands which, under high dispersion are found to consist of numerous lines very close together. Frequently, these molecular bands present a fluted appearance due to a crowding together of the component lines at a certain limit known as the head of the band and a gradual widening away from this limit. This shading

either on the red or violet side of the band head gives rise to fluted appearance which is so characteristic of the spectra of long-period variables.

The very complexity of stellar spectra, especially the solar spectrum which can be produced under very high dispersion, added to the difficulties of discovering the laws underlying atomic and molecular radiation, and it was not until 1885 that Balmer demonstrated that the wavelengths of the hydrogen spectrum can be represented by the following simple equation:

$$1/\lambda = R(1/2^2 - 1/n^2) \quad (1)$$

where λ is the wavelength, R is Rydberg's constant with a value of 109,677, and n is an integer equal to 3, 4, 5, and so on.

Quite clearly, as n increases, the value of $1/n$ will tend towards zero with the result that the higher lines in the Balmer series will become closer and closer together until they reach a limit which lies in the ultra-violet at a wavelength of about 3,640 Å.

Two further analogous series were later discovered which may be expressed by formulae of the same kind. The Lyman series occurs in the far ultra-violet, the wavelengths being given by

$$1/\lambda = R(1/1^2 - 1/n^2) \quad (2)$$

where n is 2, 3, 4 and so on.

The Paschen series lies in the infra-red and is similarly given by the expression

$$1/\lambda = R(1/3^2 - 1/n^2) \quad (3)$$

where n is 4, 5, 6 etc.

From the above equations it will be seen that the reciprocal of the wavelength is given, in each case by the difference of two terms and on this basis not only have other series of hydrogen lines been discovered in the far infra-red region of the spectrum but it is also possible to represent the series of lines due to other elements in a similar manner although as may be appreciated, the expressions concerned are far more complicated than those just given.

It is, of course, one thing to explain the positions of the various lines by means of empirical relationships like these but an entirely different matter to determine the fundamental property of the various atoms underlying them. The turning point did not come until 1913 when Niels Bohr put forward a satisfactory theoretical explanation for the spectral lines. Although Bohr's theory properly belongs to the realm of physics a brief account will be given here

since it provides an understanding of the origin of the emission and absorption lines in stellar spectra in general and in certain types of variable stars in particular.

On the Bohr theory we may picture an atom as consisting of a heavy central nucleus which is positively charged, surrounded by orbiting elections. In a normal atom the number of orbiting electrons is such that their combined negative charge exactly neutralizes the positive charge on the nucleus. The electrons revolving about the nucleus are not free to take up any orbit, however, but only certain particular ones in which the energy possessed by the electron has definite values.

Under certain conditions an electron moving in an outer orbit can jump into an inner one and in so doing it emits a definite amount of energy which appears as radiation. Furthermore, the wavelength of the emitted radiation is directly related to the energy lost by the electron during this transition. Under these conditions, therefore, an emission line will appear in the spectrum.

Conversely, if the requisite amount of energy is absorbed by the atom an electron can jump from an inner orbit to an outer one with the formation of an absorption line in the spectrum. It may be that the amount of energy absorbed is greater than that necessary to elevate an electron into its outermost orbit, for example, at very high temperatures or under the influence of radiation of extremely short wavelength. When this happens, the electron becomes dislodged altogether and the atom is then said to be ionised. Under extreme conditions an atom may lose several of its electrons in this way resulting in even higher degrees of ionisation.

When such experiments are carried out in the laboratory, such ionised atoms have very short lives indeed since there are always plenty of electrons available for recapture and even interaction with the walls of the containing vessel produce the same effect. In the outer atmospheres of stars, however, the gases are so tenuous that ionised atoms can exist for comparatively long periods and thus we find lines due to such atoms in the spectra of many stars, most usually in those of the early-spectral types where the surface temperatures are in excess of 10,000°C.

The Bohr picture of the atom, although later modified by the introduction of wave mechanics, provided an elegant explanation of the series of lines found in the hydrogen spectrum (Fig. 45) and has proved of immense value in the elucidation of atomic spectra.

When we come to apply these principles to molecular radiation, and it is this which mainly concerns us in the study of variable stars

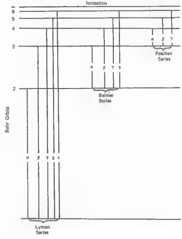


Fig. 45. *Transitions between the energy states of the hydrogen atom giving rise to the observed spectral lines*

such as long-period and semi-regular variables, we find a picture of greatly increased complexity which is apparent even in the character of the spectra of stars of types M, N, R, and S. In the simplest case of a diatomic molecule, for example titanium oxide which is present in the atmospheres of the M-type variables, not only are the electrons in motion about their respective nuclei, but the atoms themselves are in motion relative to each other.

Firstly, the atoms vibrate along the line joining their centres and secondly they are revolving about their centre of gravity (Fig. 46).

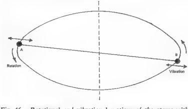


Fig. 46. *Rotational and vibrational motions of the atoms within a diatomic molecule.*

We thus have a series of lines due to transitions of electrons from one energy state to another (the electronic spectrum); another due to transitions between various vibrations states (the vibrational spectrum); and yet a third formed by transitions between various rotational states (the rotational spectrum).

Quite clearly, due to the interactions among these various states of even a simple molecule, the unravelling of molecular spectra proved to be a formidable task. Indeed, it only proved possible following the discovery by Deslandres in 1885 of certain expressions similar to those derived by Bohr, Lyman, and Paschen for atomic spectra.

Molecular spectra are found only among certain types of stars, namely those in which the surface temperature is sufficiently low for such combinations of atoms to have any existence. Even

under these conditions only the most stable molecules are formed. In G-type stars like the Sun, the surface temperature of about 6,000°C. is still too high to allow the formation of any great number of such molecules and consequently any molecular bands are extremely weak in their spectra.

It is only when it is below about 4,000°C. that they are formed in any quantity. In the long-period variables with M- and S-type spectra, molecular bands become prominent, and in the N-type variables with even lower surface temperatures they are so intense that most of the blue region of the spectrum is blotted out, and as a result such stars are among the reddest known.

CHAPTER 11

The Discovery of Variable Stars

Up to this point we have mainly confined our attention to the important contributions which may be made by variable-star observers in following the light and spectroscopic changes of known variables. We have so far said very little about the way in which these stars are discovered and how the amateur, in particular, can participate in the discovery of variable stars. The professional astronomer, having access to the largest telescopes and the most sophisticated photographic equipment, naturally has important advantages on his side, especially where the discovery of very faint variables is concerned.

It must not be thought, however, that the possessor of a small telescope, or even a pair of binoculars, can do nothing. Even today, most of the brighter novae owe their discovery to amateur observers. Nova Delphini (1967), Nova Vulpeculae (1968), and Nova Scuti (1970) discovered by Alcock, and Novae Serpentis (1970) and Aquilae (1970) both discovered by Honda, are examples of such discoveries.

The Early Discoveries

During the first two or three centuries following the discovery of Mira by Fabricius, the number of known variable stars was comparatively small and all were found by carefully comparing the brightnesses of the stars over an extended period. Owing to the obvious limitation in the sizes of the telescopes then available, only the brighter variables could be followed through the whole of their light cycles, those with large amplitudes being lost completely whenever they passed through their faint minima.

The observation and discovery of variable stars was first put on a systematic basis by Argelander in the mid-nineteenth century. About this time, too, the use of photography in astronomy became more widespread, resulting in the discovery of many more variables. Indeed, it is true to say that more variable stars were discovered

in the two decades following the publication of the Bonner Durchmusterung charts of the northern heavens than in the three preceding centuries.

Since the beginning of the present century, an extensive programme of photographing several selected fields within the Milky Way at regular intervals has greatly increased the number of known variables. Most of the fainter novae, particularly those in Sagittarius and Scorpio, have been discovered by this means, but since there is inevitably a delay between the processing of the photographic plates and their detailed examination, such novae are often only recognized several years after the maximum has occurred. As there may be many hundreds, if not thousands, of stars on a single plate, the problem of determining which stars are variable in brightness has to be solved by special techniques. The simplest and most widely-used method is by means of an instrument known as the blink microscope.

The Blink Microscope

The blink microscope or stereo-comparator is an instrument which enables two photographic plates of the same region taken by the same telescope but at different times, to be examined alternately in fairly rapid succession. The plates are placed side by side on a stage and illuminated alternately several times a minute. This rapidly changing presentation of the two plates to the eye facilitates the discovery of variable stars and novae.

In the case of the various types of variable star, the brightness will be different on each plate and the image will appear to pulsate quite markedly and rapidly in brightness. The novae, although of much rarer occurrence, are even more readily picked out, even among hundreds of stars since the image is usually present on one plate and not on the other. As the result the star will blink in and out under the changing illumination.

In some regions of the sky, notably among the selected Milky Way fields, large numbers of variables are found on a single plate. Naturally it is out of the question to follow all of these newly-discovered variables sufficiently closely to determine accurate characteristics of their light curves. The short-period stars such as the eclipsing variables, RR Lyrae stars, and certain of the Cepheids may be fairly readily assigned to their respective classes. Their preliminary periods may also be determined.

The parameters given for those stars having longer periods – the long-period and semi-regular variables – must inevitably be subject

to some degree of uncertainty. Unfortunately, in most cases, their general faintness makes it difficult to obtain good spectra which would otherwise prove useful in determining their type. From the published data it would appear that by far the greater proportion of the variables which have been discovered during these photographic surveys are RR Lyrae, long-period, and eclipsing variables. Although it may be argued that this could be a selective effect due to their characteristics being more readily evaluated than those of the irregular variables such as the dwarf novae, RV Tauri, and R Coronae Borealis stars, this is unlikely. It seems more probable that the latter variables are of much rarer occurrence within the galaxy than the former.

Regions to Observe for New Variables

The amateur observer who wishes to discover new variable stars for himself should not be discouraged by the fact that there is this professional coverage of the heavens. It is clearly impossible for large observatories to devote sufficient observing time on the big telescopes to patrol the whole of the sky and obviously there must be large regions which are not adequately covered. A study of the *General Catalogue of Variable Stars* will soon reveal that certain constellations such as Aquila, Centaurus, Corona Australis, Cygnus, Ophiuchus, Sagittarius, and Scorpio each contain several hundred known variable stars of all classes. Other constellations, for example, Andromeda, Aquarius, Böotes, Capricornus, Draco, Eridanus, Leo, Serpens, Ursa Major and Virgo, contain relatively few.

This is clearly not due to the areas covered by these constellations for they are all comparable in size. The former are, of course, those constellations which lie close to, or astride, the Milky Way and contain very rich star fields. For this reason, they are also those constellations which have been fairly extensively covered by the photographic surveys. The other constellations just mentioned lie well away from the Milky Way and are comparatively sparsely populated with stars.

For these two reasons therefore, the amateur should concentrate his attention upon those constellations which are well removed from the Milky Way. Even here, most of the brighter variables have been known for many decades and for success, it is necessary to photograph several regions of the sky at intervals of perhaps a week or so. As this will be work prior to determining the type of variability, it is not necessary to use special filters to obtain photovisual estimates.

Of the two methods described in Chapter 9, that of focal plane photography is the better for this purpose since it gives sharp images on the film. Exposure times of twenty minutes will yield images of stars which are about two magnitudes fainter than those which can be seen visually. If possible, the prints should be of the 10″ × 8″ size although satisfactory results can be obtained with half-plate size enlargements.

The prints may then be compared using a hand magnifier, the positions of any images which either differ appreciably in brightness, or which appear on certain photographs and not on others, being carefully noted. Undoubtedly, some of these will be spurious images, being nothing more than defects on the film, but once a series of photographs of the same region has been built up, it should be comparatively simple to eliminate these. As the observer becomes more proficient in this work and the available data accumulates, it will sometimes be possible to hazard a guess as to the probable nature of a particular variable, perhaps even to gain an approximate estimate of the period.

There are, however, certain pitfalls when it comes to estimating both type and period of which the observer must be aware. Short-period variables such as the RR Lyrae stars and eclipsing variables are difficult to identify correctly from plates taken a week or so apart. When these variables are sufficiently bright, they may be identified by the method given earlier in Chapter 9 by making a series of exposures twenty minutes or so apart on the same film. The long-period Cepheids and those semi-regulars at the short end of the period range generally have small amplitudes and are not only difficult to pick out but far from easy to assign to their correct class from scattered photographic observations taken at weekly intervals. Where the variable is bright enough to be observed visually, such observations may be used to complement the photographic estimates and a visual light curve plotted. From this it should be possible to place the variable into its correct category.

The long-period variables are more readily recognizable from such a collection of photographs since their light variations are quite distinctive and their amplitudes generally exceed five magnitudes. Here again, however, it is possible to mis-classify a variable. A case in point is AR Andromedae, classed as a long-period variable by Chernova with a period of 265 days, an M-type spectrum and a photographic magnitude at maximum of 11·5. More recent spectroscopic work by Makarian suggested that it was a U Geminorum variable with a mean period of about 65 days, the star showing a high ultra-violet excess at maximum. The light curve as obtained by the author from 1968 to 1969 confirms the latter classification.

The chance of discovering one of the much rarer types of variable, for example of the R Coronae Borealis or U Geminorum class, is admittedly not as great as for the other types due to their much less frequent occurrence. In particular, the majority of the dwarf novae are very faint objects even at maximum. However, such finds may still be made. One of the most recent of the U Geminorum stars to be discovered, IR Geminorum, happens to be among the brighter members of this small group with a photographic range of 10·8 to 13·1 magnitude, well within the reach of a moderate aperture.

The Nova Patrol

For those observers who possess only binoculars or a small telescope, the search for novae may ultimately prove to be the most rewarding although even here, the prime requisite is patience. As we have already seen, the novae concentrate along the boundaries of the Milky Way, and a comparison of the numbers actually observed and those which have already been calculated to occur each year shows that many must inevitably have been lost altogether. Others are discovered on patrol plates long after the maximum occurred and of these many are binocular objects, brighter than ninth magnitude at the time of the outburst.

In a clear sky, binoculars will show stars down to around ninth magnitude but this is clearly near the limit and it is better to confine oneself to observing stars down to about seventh magnitude. A few observers have the ability for familiarizing themselves with all of the stars down to this magnitude in most of the constellations bordering the Milky Way, but these are in the minority. Until the observer can attain this high degree of familiarity, it is better to concentrate upon one or two regions and learn the positions of all the stars down to the sixth or seventh magnitude within these areas.

These chosen regions should be swept slowly with binoculars on every possible night. Should a star be noticed which was not present on previous occasions, its position and approximate magnitude must be checked. If the constellation happens to lie on the Zodiac there is always the possibility that it may be a minor planet. Any movement against the background stars in a period of a couple of hours or so will be sufficient to confirm this unless the asteroid

happens to be at its stationary point when a longer period will be required before this possibility can be eliminated.

Having ascertained that the object is not an asteroid, the position of the suspected nova must be checked with a star atlas. It is unlikely that the observer will possess the B.D. charts which show the stars down to around 9·5 magnitude but more recent atlases are now available. Some, like the Bayer-Graff atlas are directly comparable with the B.D. Others are more up to date both in the star positions and the adopted magnitudes and of these may be mentioned the *Atlas Coeli*, *Atlas Ecliptalis*, and the *Atlas Borealis*.

If the star is not given in these atlases, and it is preferable to check in at least two of them as omissions are known in them all, then it may be assumed that the object is a nova. The nearest professional observatory should then be informed as soon as possible giving details of the magnitude and the position of the star. The latter should, of course, be as accurate as possible. The principal observatories throughout the world are then informed by the I.A.U. by telegram so that comprehensive observations may be carried out with the minimum of delay.

If possible, the brightness of the star should be estimated the next night when any marked variation in brightness will provide added confirmation of its nature. Indeed, if there are sufficient hours of darkness left immediately after discovery, the star may be observed two or three times since there is always the possibility that it has been caught on the pre-maximum rise and such estimates are of very great value. As it is unlikely that an accurate sequence of comparison stars will be available at the time of discovery, the stars used for preliminary magnitude estimates should be carefully noted so that the provisional estimates may be revised once such a sequence has been set up.

CHAPTER 12

Some Recent Novae

Except for the occasional galactic supernova, the novae are among the most spectacular of all the variable stars. As is well known, the estimated number of novae appearing in the galaxy is between twenty and thirty per annum. Unfortunately the faintness of many of these at maximum and the fact that it is impossible to predict where or when a nova will appear (except that the majority are found in, or close to the Milky Way) militates against more than a very small proportion of these being discovered at the time of the outburst.

A large number are not discovered until several years after they have attained maximum brightness being found on patrol plates taken of the rich star fields bordering the Milky Way. It is all the more encouraging, therefore, to find that seven bright novae have been discovered in the northern hemisphere during the past decade. That these novae were discovered by amateur observers also confirms the immense value of continuously patrolling those regions along the galactic plane with no more instrumental aid than a pair of binoculars. As further confirmation of this, it may be noted that three of these novae were discovered in England by Alcock and two in Japan by Honda.

Nova Herculis (1960)

This nova was discovered on the borders of Hercules and Aquila by Hassel on 7 March, 1960 when it was about fifth magnitude. This was the first naked-eye nova to be discovered since the completion of the National Geographic Society-Palomar Sky Survey and it afforded an excellent opportunity to attempt an identification of the nova before the outburst. A photograph of the nova was taken with the 60-inch reflector at Mount Wilson Observatory on 21 March to obtain an accurate position for this star and this was then compared with the Survey Atlas showing the region of the nova. Although Kraft and Cragg found a faint image of sixteenth

magnitude on the red and blue plates 344-E and 344-O taken on 12 August, 1952, certain difficulties were encountered when trying to make a positive identificaton in that the image did not appear to be perfectly circular as were most of the others suggesting that this might be a multiple star.

Fortunately, an earlier pair of red and blue plates, 322-E and 322-O had been taken on 22 August, 1951 but rejected owing to a flaw in one corner. These showed quite clearly that the image was that of a triple star, the components being of about eighteenth magnitude. Moreover, one of these which lay closest to the position of the nova was variable in brightness with an amplitude of 2·5 magnitudes in the blue and 2·0 magnitudes in the red. It is now generally accepted that this faint star represents the pre-nova stage of Nova Herculis (1960).

Photographs of the region were also taken by Honda at the Kurasiki Observatory in Japan showing that the star was fainter than tenth magnitude as late as 27 February, 1960 but had a photographic magnitude of 3·0 on 4 March. By 7 March, when discovered visually by Hassel, the patrol plates showed that it had declined to 4·4 magnitude. It would thus appear that the nova was approximately four days past the initial outburst when discovered.

Shortly after discovery, several excellent spectrograms had been taken at the Royal Greenwich Observatory showing the very characteristic broad emission lines of hydrogen. The Doppler shift to the violet indicated a velocity of approach of about 800 kilometres per second which is quite typical of a nova.

The light curve, too, exhibited the usual characteristics of a fairly fast nova although the star remained around the fifth magnitude for some weeks after the outburst. By the end of the year, however, it had declined to 11·5 magnitude, this gradual fading continuing throughout 1961 (Fig. 47). By the beginning of 1962 it had reached fourteenth magnitude and was visible only in moderately large instruments.

NOVA HERCULIS (1963)

The second bright nova of the last decade was discovered on the borders of Hercules and Lyra by Dahlgren on 6 February, 1963 and independently by Peltier on the same night. When found, the nova had a visual magnitude of 3·9 but, as in the case of Nova Herculis (1960), patrol plates taken at Tokyo give some valuable indication of its behaviour shortly before discovery. The star was fainter than tenth magnitude on 20 January, 1963 but had

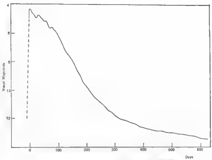


Fig. 47. *Light curve of Nova Herculis (1960)*

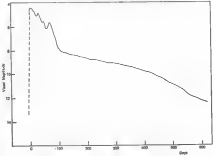


Fig. 48. *Light curve of Nova Herculis (1963)*

risen to 8·0 magnitude on 26 January and was about maximum brightness of 3·1 magnitude on 30 January. By 4 February it had declined somewhat to 3·9 magnitude so once again it would seem that the discovery was made about ten days after the outburst.

The light curve (Fig. 48) shows several interesting features and if we accept the usual arbitrary criterion for fast novae, namely that the initial decline of three magnitudes takes place in less than 100 days, then Nova Herculis (1963) certainly qualifies for assignment to this class. Not only are several minor fluctuations present during the initial decline but photoelectric observations made on 27 March and 29 March show very rapid changes in brightness of the order of 0·2 magnitude.

Like the previous nova, the spectrum of this star taken shortly after the initial maximum shows broad emission lines of hydrogen with Doppler shifts corresponding to 700 to 900 kilometres per second. Following the initial, fairly steep drop in brightness, the rate of decline diminished appreciably and this was reflected in the comparatively slow changes in the spectrum.

Nova Delphini (1967)

This particular nova, discovered by Alcock on 8 July, 1967 has proved to be one of the most unusual of all novae. At the time of discovery, it was a star of 5·8 magnitude but as in many similar cases, a search of photographic plate collections of several observatories revealed a great deal of information concerning the immediate pre-nova stage. Indeed, in the case of Nova Delphini (1967) this also revealed that the nova was a star of 11·9 magnitude which was slightly variable over the period from 1890 to June 1967. Owing to its comparative brightness before the outburst, spectra of this star had been obtained as far back as 1965 and an objective prism spectrum taken in 1960 revealed it to be a star of spectral type OB, a very hot star with a continuous spectrum containing no absorption lines.

On 7 June, 1967 this star commenced a remarkably slow increase in brightness which is well brought out in the light curve (Fig. 49). The brightness levelled off on 5 July to 5·8 magnitude and this very slow rise to the initial maximum of 30 days was one of the first peculiarities to be discovered concerning this particular nova. This, coupled with the small amplitude of only six to seven magnitudes, is most unusual for a nova.

For the first 150 days or so following the rise to maximum, Nova Delphini (1967) behaved in a similar manner to a typical slow

nova remaining at a broad maximum with only minor fluctuations. In this respect, it closely resembled Nova DO Aquilae (1925) although at this phase it was some four magnitudes brighter. Then on 5 December, a further increase in brightness set in with the star reaching 3·5 magnitude. Almost at once, however, it began to fade, returning to fifth magnitude by the end of the month. Throughout January 1964, the nova remained at essentially the same magnitude and then, on 3 February, a second, steeper rise commenced with the star again brightening to 3·5 magnitude. Even as late as May 1968, almost a year after the initial rise, the nova brightened slowly and was a magnitude brighter than when first discovered. Inevitably, of course, a slow decline set in but even now, more than three years after the outburst, the star is more than two magnitudes above its original brightness. Such peculiar behaviour is almost unprecedented in a nova of small amplitude being parallelled only by η Carinae.

Whether Nova Delphini (1967) is a recurrent nova is still open to question. All that can be said at the moment is that there have been no outbursts over the period from 1890 and the light curve is unlike those of the recurrent novae which have so far been observed.

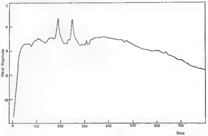


Fig. 49. *Light curve of Nova HR Delphini (1967)*

As might be expected, the spectroscope has provided a great wealth of information concerning this particular star. Spectrograms taken in July 1967 show great detail in the metal lines particularly in the fine structure of the line due to singly ionised calcium at 3933 Å. In addition to the bright emission line, a complex series of absorption lines displaced to the violet indicate that shortly after the outburst, four distinct masses of relatively cool material were ejected with velocities of 810, 700, 630, and 540 kilometres per second respectively. During the increase in brightness on 5 December, another shell of gas was thrown out by the star dispelling the dense cloud of material formed by the previous explosion. This peculiar behaviour was evidently repeated once more in February 1968. The present picture we have, therefore, of the outburst of June 1967 is one in which four relatively minor explosions, spread over a period of about three weeks, occurred rather than one major explosion as is common in the novae.

Nova Vulpeculae (1968)

On 15 April, 1968 Alcock discovered his second nova, this time in Vulpecula. At the time of discovery it was a little brighter than 5·0 magnitude and reached its maximum brightness two days later. According to photoelectric observations made at Teramo Observatory on 17 August the star attained 4·3 magnitude but almost immediately a rapid decline began and unlike Nova Delphini it proved to be a typical fast nova with no marked deviations from the norm. The decline gradually diminished in rapidity with only minor fluctuations (Fig. 50).

The spectrum at maximum brightness still showed several characteristics of the pre-nova spectrum with numerous absorption lines and has been classified by Rosino as peculiar F5–F8. The Doppler shift measured from the absorption lines yielded a velocity of approach of about 670 kilometers per second. By the following day the principal nova spectrum had developed with several emission lines present and an increased Doppler shift corresponding to an approach of 1,380 kilometres per second. In addition to the usual lines, stationary lines of calcium were also present arising from interstellar matter lying between us and the star.

The pre-nova stage has been identified by Herbig as a component of a faint double star of 16·5 magnitude and it is now quite clear that this star is not the remnant of the nova of 1670 which lies quite close to it. When first discovered, the suggestion was put forward that this might be a second outburst of Nova Vulpeculae (1670).

Perhaps of greatest significance is the fact that the infra-red spectra taken of this star close to maximum revealed the presence of the infra-red triplet of singly ionised calcium. This is the first time that these lines have been identified in the spectrum of a nova although they are well known in the case of many long-period variables. From the fact that Nova Vulpeculae (1968) appears to be quite an ordinary nova, it seems likely that these lines are a common occurrence in novae and that they have been missed in the past simply because infra-red spectrograms have not been obtained sufficiently close to the time of maximum brightness.

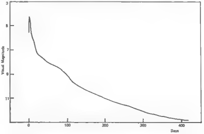


Fig. 50. *Light curve of Nova Vulpeculae (1968)*

Taking into account the steepness of the decline which was of the order of 3 magnitudes in a month, the mean absolute magnitude at maximum has been estimated as −7·8 and from the amplitude of 12 magnitudes, a photographic absolute magnitude of +4 has been derived. All of these values are therefore very similar to those of other novae of this type. At the present time, this nova is quite faint, being about fourteenth magnitude and moderately large instruments are necessary for its continued observation.

Nova Serpentis (1970)

1970 saw the discovery by amateur observers of three bright novae, the first of which was found by Honda in Serpens on 14 February when it was of the fifth magnitude. By the following night it had brightened slightly to 4·6 magnitude where it remained until the middle of March with only minor changes in brightness after which a slow fading commenced. There was then a short transition stage characterized by rapid, but apparently random, fluctuations before the star began a steep decline in late April, fading by 3 magnitudes in 4 days. This is clearly shown in Fig. 51.

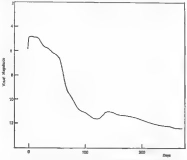


Fig. 51. *Light curve of Nova Serpentis (1970)*

A slow recovery in August was then followed by a steady decline with only small fluctuations in brightness. A photograph taken of the region by Pennell on 22 August, 1968 shows a faint star of 13·6 magnitude in the position of the nova and it appears quite probable that this represents the pre-nova stage. If this is the case, then the amplitude of about 9·5 magnitudes, although small, is within the normal range for a nova of this type.

Spectrograms taken of this star shortly after maximum and when the principal nova spectrum had developed, show emission lines with a Doppler shift to the violet corresponding to a velocity of about 1,200 kilometers per second. The nova is still above its minimum but judging from its type, it seems doubtful if any further major developments will occur.

Nova Aquilae (1970)

Of the seven novae described in this chapter, this has proved to be the faintest at maximum. When discovered, again by Honda, on 14 April, it was only of eighth magnitude and although a rise of 1 magnitude was reported by the following night, the star fell almost immediately to 8·1 magnitude and had reached 8·8 magnitude by the beginning of May.

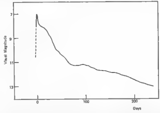


Fig. 52. *Provisional light curve of Nova Aquilae (1970)*

The preliminary light curve (Fig. 52) is indeed indicative of a typical fast nova. So far, no positive identification of the pre-nova stage has been made but if the amplitude is normal for this class of nova, the star cannot have been much brighter than sixteenth magnitude before the outburst.

Nova Scuti (1970)

This is the third nova to be discovered visually by Alcock using 11 × 80 binoculars and was found on 31 July, 1970. At the time of discovery it was estimated at 6·9 magnitude but on the following

night under hazy conditions, it had faded by a magnitude. Unlike the majority of novae at maximum, the star was decidedly yellow in colour.

A slow decline set in almost at once and from preliminary observations it would appear that this star too, is a typical fast nova (Fig. 53) although continued observation will be necessary to confirm this.

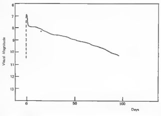


Fig. 53. *Provisional light curve of Nova Scuti (1970).*

The discovery of so many bright novae either visually or photographically by amateurs during the past decade once again underlines the importance of a nova patrol. Although the time spent in such work is enormous and the reward very occasional, the fact that one observer has discovered three novae while another has two such discoveries to his credit indicates that the rewards are there, provided one has the patience to undertake this type of study and to learn the positions of the stars in these fields down to about eighth magnitude.

Glossary

Absolute magnitude. The apparent brightness a star would have if it were at a standard distance of 10 parsecs (32·6 light years) from us, thus providing a measure of its intrinsic luminosity.

Absorption spectrum. A spectrum consisting of dark lines superimposed upon a brighter continuum produced by a cooler gas absorbing energy from a source at a higher temperature lying behind it.

Algol variable. An eclipsing variable in which the two components are sufficiently widely separated for them to be essentially spherical in shape. Named after the prototype β Persei. The light curves are characterized by having comparatively flat maxima.

Aphelion. The point in the orbit of a binary system when the two components are at their greatest distance apart.

Apparent magnitude. The brightness of a star or other celestial object as it appears to a terrestrial observer taking no account of distance.

Apsidal rotation. A slow rotation of the line of apsides in a binary system due to the fact that the orbit is not a closed one. In eclipsing variables it manifests itself in a movement of the secondary minimum with respect to the primary minima.

Apsides (line of). The line joining the extremities of the major axis of an orbit. Theoretically this line may be extended indefinitely in both directions.

RW Aurigae variables. Irregular variables, usually of spectral type G, found in very large associations and normally intimately connected with gaseous nebulae such as that in Orion (see T Orionis variables).

Averted vision. Observing with the more light-sensitive outer part of the retina, that is, not looking directly at the object. This has the advantage of making very faint stars visible.

Binary system. A double star, the components of which are close enough to be bound together by gravity and revolving about a common centre of gravity.

Bias. A source of error in variable-star observation due to an unconscious expectation on the part of the observer that a variable will behave in a certain way based upon past estimates.

Z Camelopardalis variable. A dwarf nova (*see below*) in which the light curve is characterized by unpredictable periods of virtually constant brightness intermediate between maximum and minimum.

β Canis Majoris variable. A very hot, white star having a short period and very small amplitude. The light curves are similar in shape to those of the Cepheids.

Cepheid variable. A pulsating star usually with a constant period named after the brightest representative δ Cephei. Two classes are usually distinguished – the classical Cepheids with periods between 1·5 and 28 days and the long-period Cepheids with periods in excess of 28 days.

Circumpolar variable. A variable star which lies sufficiently close to the north or south celestial pole to be visible throughout the year from the northern and southern hemispheres respectively.

Colour index. The difference in magnitudes between the photographic and visual magnitudes of a star. Blue stars have negative and red stars have positive colour indices.

Comparison star. A star of known constant brightness against which the variable is compared.

Continuous spectrum. A featureless spectrum consisting merely of a band of colours emitted by an incandescent solid, liquid, or gas under high pressure.

R Coronae Borealis variable. An irregular variable whose light curve is typified by unpredictable decreases in brightness, the spectrum showing an over-abundance of carbon and a marked deficiency of hydrogen.

Dark adaptation. Adaptation of the eye to darkness following a period of relatively bright illumination, essential for satisfactory observation of faint objects.

Doppler effect. A change in the wavelength of sound, light, and other radiation due to the relative motion of the emitting source and the observer.

Dwarf nova. A variable star, typified by U Geminorum (*see below*) subject to nova-like outbursts at unpredictable intervals, usually between 16 and 300 days.

Eclipsing variable. A binary system in which the orbital plane lies in the line of sight resulting in the components eclipsing each other during one revolution about the common centre of gravity.

Emission spectrum. The spectrum normally produced by an incandescent gas consisting of bright lines against a dark background.

Epoch. The date for which an astronomical chart or catalogue has been calculated. Since precession and proper motion produce changes in position it is essential that this should be given for comparison at future epochs.

Eruptive variable. A variable star in which the observed light variations are produced by some eruptive process within the star, for example the dwarf novae, novae, and supernovae.

Extrinsic variable. A variable whose light changes are due to external factors and not to some property of the star itself, for example an eclipsing variable.

Flare star. An intrinsically faint red dwarf which exhibits occasional brief, rapid increases in brightness reminiscent of solar flares.

Fractional method. A means of estimating the magnitude of a variable star by judging its brightness as a fraction of the interval between two comparison stars, one brighter and one fainter than the variable.

Fraunhofer lines. The absorption lines in the solar spectrum rediscovered in 1814 by Fraunhofer and lettered by him.

Gas stream. A stream of gas frequently present in binary-star systems and flowing from one component to the other through the Inner Lagrangian point (*see below*).

U Geminorum variable. The more common type of dwarf nova (*see above*) in which the light curves show no evidence for any period of constant intermediate brightness thereby distinguishing them from the Z Camelopardalis variables.

Harvard sequence. A sequence of stellar spectra arranged in order of decreasing surface temperature based upon photographic spectra taken with an objective prism.

Hertzsprung-Russell diagram: A diagram obtained by plotting the absolute magnitudes of the stars against their spectral types.

Inner Lagrangian point. The point in a binary system where the Roche lobes (*see below*) meet. It is through this point that any transfer of mass from one component to the other takes place.

Intrinsic variable. A variable star in which the observed variations in brightness are produced by some property inherent in the star itself, for example, the pulsating and eruptive variables.

Irregular variable. A general term covering those variable stars for which no trace of periodicity can be discovered in their light changes.

Julian Date. The number of days which have elapsed since the beginning of the Julian Period.

Julian Period. A method used to calculate exact intervals between events widely separated in time. For astronomical purposes the Julian Period began on 1 January, 4713 B.C.

Light Curve. The curve obtained by plotting the magnitude of a variable star against time thereby defining the nature of the light variations.

Long-period variable. A red star in which the light changes are relatively slow and show a certain degree of regularity. The periods usually lie between 100 and 700 days, the majority being about 300 days. The amplitudes are usually large for a variable star.

RR Lyrae variable. A pulsating variable with periods less than 1 day. Sometimes termed cluster variables owing to their preponderance in the globular clusters.

β Lyrae variable. An eclipsing system in which the components are comparatively close together resulting in a marked distortion of their shapes owing to the high gravitational and tidal forces present. The light variations are therefore continuous

Magnetic variable. A star in which the light changes are also accompanied by variations in the strength of the magnetic field.

Main sequence. A line on the Hertzsprung-Russell diagram on which most of the stars fall, the Sun being a typical main sequence star.

Nebular variable. A variable star found associated with either dark or bright nebulosity and including the RW Aurigae (*see above*), T Orionis, and T Tauri variables (*see below*).

Nova. A star which flares up from obscurity without warning usually returning to its original brightness within months or years of the outburst.

T Orionis variable. An irregular variable in which the light variations are erratic and sometimes rapid, always associated with bright nebulosities, mainly to be found in the Orion Nebula.

Perihelion. The point in the orbit of a binary system at which the two components are at their closest, the opposite of aphelion.

Period. The interval between successive maxima, or minima, of a variable star; the mean period in the case of a semi-regular variable being that averaged over a number of cycles.

Period-luminosity law. An expression relating the period of an RR Lyrae star or Cepheid with its absolute magnitude thereby allowing distances to be estimated.

Personal equation. The amount by which an observer's estimates differ from the mean value, found especially in observations of red stars when it represents a measure of the colour acuity of the observer's eye.

Photoelectric magnitude. The magnitude of a star as determined with a photoelecric cell.

Photographic magnitude. The brightness of a star as determined by the photographic plate with blue stars photographing brighter and red stars fainter than visually, by an amount depending upon their spectral type.

Photovisual magnitude. The magnitude, approximating that of the visual, obtained photographically using special orthochromatic or panchromatic emulsion and an isochromatic filter corresponding to the yellow region of the spectrum.

Pogson's step method. A means of estimating the brightness of a variable star by training the eye to distinguish in steps of a tenth of a magnitude and having the advantage that the variable is compared with only one comparison star at a time.

Population I stars. Relatively young stars like the Sun found preponderantly in the spiral arms of galaxies and representing a second stage in star formation.

Population II stars. The older stars found mainly in the nuclei of the galaxies and in the globular clusters, being the first stars to form from the primal gas cloud.

Position angle error. An error introduced in determining the magnitude of a variable star by comparing it with a comparison star lower in the field of view.

Pulsating variable. A variable in which the changes in brightness are due primarily to an alternate expansion and contraction of the star which in turn leads to variations in the surface temperature, such pulsations being either regular as in the RR Lyrae and Cepheid variables or irregular as in the semi-regular and long-period stars.

Purkinje Effect. The difference in brightness found visually when red and white point sources of light of equal intensity are brightened or dimmed by the same amount.

Radial velocity. The apparent velocity of a star or the gases ejected from a nova directly towards or away from the observer and measured by the Doppler effect being usually expressed in kilometres per second.

Radial velocity curve. The curve obtained by plotting the radial velocity against time.

Recurrent nova. A star in which the nova outburst occurs at fairly frequent intervals of the order of tens of years, the amplitude in general being smaller than in the novae.

Reflection effect. An irregularity in the light curve of an eclipsing variable due to the hemisphere of the fainter star which faces the brighter companion being brighter than the other.

Resolving power. The ability of a telescope to separate two very close stars, being proportional to the aperture.

Roche lobe. A region surrounding a star, the size and shape of which depends upon the mass of the star and any external gravitational fields; the Roche lobes of a close binary being dumb-bell shaped and meeting at the Inner Lagrangian point (*see above*).

Semi-regular variable. A variable star in which the period is only approximately regular, often with a secondary period superimposed upon the primary cycle.

Sequence. A series of comparison stars arranged in order of decreasing brightness and covering the entire range of the variable.

Standard deviation. A statistical method of measuring the dispersion of a series of values about the arithmetic mean.

Standstill. The portion of the light curve of a Z Camelopardalis variable (*see above*) during which the star remains for an indefinite time at some brightness intermediate between maximum and minimum.

Supernova. An exploding star of much rarer occurrence than the ordinary novae and with an amplitude far greater.

T Tauri variable. An irregular red dwarf variable, usually with an M-type spectrum which is closely associated with dark nebulosity.

RV Tauri variable. A semi-regular variable with a light curve usually characterized by alternate deep and shallow minima.

W Ursae Majoris variable. An eclipsing system with components very like the Sun; probably the precursor of the dwarf nova stars.

Variable star. A star which shows a variation in its brightness with time, the variation being either regular or totally irregular.

Visual magnitude. The brightness of a star as estimated by the eye.

White dwarf. A star having the same mass as a normal star but with only planetary dimensions resulting in fantastically high densities, frequently found as one component of the old nova and dwarf nova systems.

Zodiacal variable. A variable star situated in one of the zodiacal constellations and consequently unobservable during the time the Sun is passing through that particular constellation.

Appendix

WITH CHARTS AND SEQUENCES

Appendix

The series of charts and sequences which follow are designed to cover a variety of variable stars from naked-eye variables to those which require large instruments for their observation.

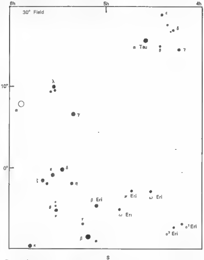
When using these charts it must be remembered that those for the brighter stars have south at the bottom since they will be used either with the naked eye or binoculars. The fainter variables will naturally be observed with an astronomical telescope and here the field is inverted.

The scale of the charts varies quite considerably from 30° fields for the bright stars down to 20′ for the faintest.

In all cases the position of the variable is marked by a small circle.

Betelgeuse (α Orionis)

A semi-regular variable with a range of 0·4 to 1·3 magnitude and an average period of 2,070 days.

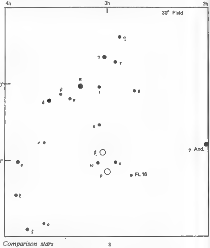


Comparison stars

Star	Magnitude	Star	Magnitude
β Ori	0·34	γ Ori	1·70
α Tau	1·06		

Algol (β Persei)

The prototype of the Algol eclipsing variables with a range of 2·20 to 3·47 magnitude and a period of 2·86731 days.

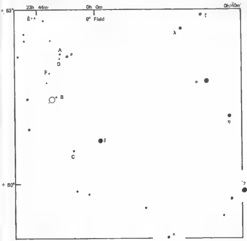


Comparison stars

Star	Magnitude	Star	Magnitude
α Per	1·90	δ Per	3·10
ζ Per	2·91	η Per	3.93
ε Per	2·96	τ Per	4·10
γ Per	3·08		

ρ Cassiopeiae

An irregular variable with a light curve similar in many respects to the R Coronae Borealis stars. The range in brightness is 4·1 to 6·2 magnitude.



Comparison stars

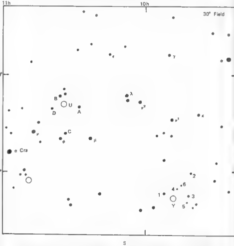
Star	Magnitude	Star	Magnitude	Star	Magnitude
ζ Cas	3·72	σ Cas	4.93	C	6·51
κ Cas	4·24	τ Cas	5·09	D	7·01
θ Cas	4·52	A	5·69	E	7·22
λ Cas	4·88	B	6·05	F	7·48

U Hydrae

is a semi-regular variable with a range of 6·9 to 7·9 magnitude.

Y Hydrae

is a semi-regular variable with a range of 6·9 to 7·9 magnitude. This star has a double period; a primary one of 95 days and a longer secondary one of about 1,200 days.



Comparison stars for U Hydrae			
Star	Magnitude	Star	Magnitude
μ Hya	4·06	B	5·88
ν² Hya	4·72	C	6·21
φ Hya	5·11	D	6·39
A	5·51		

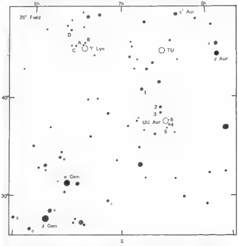
Comparison stars for Y Hydrae			
Star	Magnitude	Star	Magnitude
1	6·28	4	7·19
2	6·70	5	7·51
3	6·82	6	7·63

UU Aurigae

is a semi-regular variable with a long mean period of 3,400 days and a range of 5·1 to 6·8 magnitude.

Y Lyncis

is an irregular variable with an ill-defined mean period of about 250 days. The range of this star is from 7·2 to 7·8 magnitude.

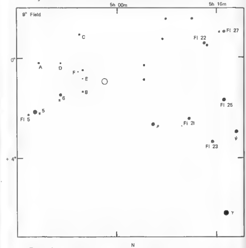


Comparison stars for UU Aurigae			
Star	Magnitude	Star	Magnitude
1	4·98	4	6·63
2	5·30	5	6·89
3	5·71	6	7·13

Comparison stars for Y Lyncis	
Star	Magnitude
A	6·58
B	6·81
C	7·33
D	7·62

W Orionis

a semi-regular variable, varies between 5·8 and 7·3 magnitude in a mean period of 200 days. There is some evidence of a secondary wave, about 2,000 days in length, superimposed upon the primary cycle.

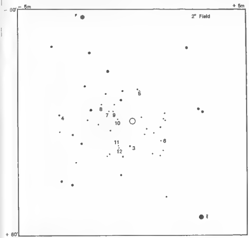


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude
π^5 Ori	3.9	A	5·9	D	7·3
π^6 Ori	4·7	B	6·2	E	8·3
Fl 27 Ori	5·2	C	6·6	F	8·8
Fl 5 Ori	5·7				

TX Cygni

is a classical Cepheid with a period of 14·7079 days and a range of from 9·6 to 11·7 magnitude.

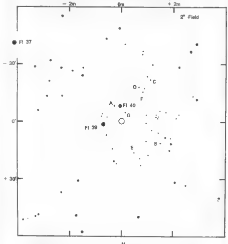


Comparison stars

Star	Magnitude	Star	Magnitude
ξ Cyg	3·92	7	9·6
ν Cyg	4·04	8	9·9
3	8·0	9	10·2
4	8·4	10	10·5
5	8·8	11	11·0
6	9·2	12	11·3

SW Geminorum

with a range of 9·2 to 10·6 magnitude, is a long-period variable with the relatively long mean period of 700 days.

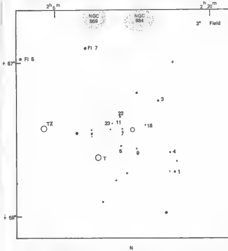


Comparison stars

Star	Magnitude	Star	Magnitude
A	8·88	E	10·11
B	9·41	F	10·52
C	9·72	G	10·78
D	9·90		

S Persei

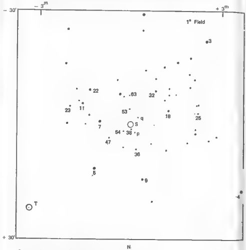
has an extreme range of 7·2 to 12·2 magnitude but the light variations are complex in this semi-regular variable and there appear to be two interacting periods of 810 and 916 days.



Comparison stars for 3° field

Star	Magnitude	Star	Magnitude	Star	Magnitude
1	7·39	7	8·38	18	9·53
3	7·78	9	8·72	22	9·53
4	8·10	e	8·88	22	9·92
5	8·30	11	9·07		

The 1° field for S Persei showing fainter comparison stars for use when the variable is around minimum brightness.

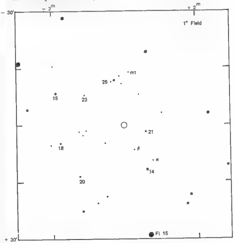


Comparison stars for 1° field

Star	Magnitude	Star	Magnitude	Star	Magnitude
25	10·08	47	11·61	o	12·84
32	10·54	53	11·80	p	13·29
36	10·68	54	11·87	q	13·81
38	11·33	63	12·44		

V Ursae Majoris

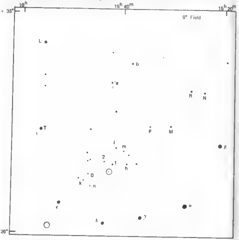
is a semi-regular variable having a range of 9·6 to 11·0 magnitude in a mean period of 210 days.



Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude
14	9·2	21	10·6	mt	12·1
15	9·4	23	11·0	α	12·3
18	9·8	25	11·3	β	12·6
20	10·1				

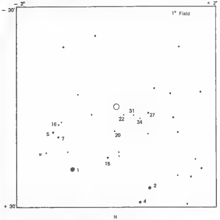
R Coronae Borealis
is the prototype star of this small group of variables. The exereme range is 5·8 to 14·4 magnitude. For most of the time this star remains around 6·0 magnitude.



Comparison stars for 9° field

Star	Magnitude	Star	Magnitude	Star	Magnitude	Star	Magnitude
T	4·73	d	6·15	g	7·63	m	8·88
L	5·50	M	6·57	h	7·93	2	8·88
b	5·56	e	6·72	k	8·28	n	9·20
c	5·94	1	7·18	l	8·60	4	9·36

The 1° field for R Coronae Borealis showing the positions of the comparison stars which may be used when the variable is passing through a deep minimum.

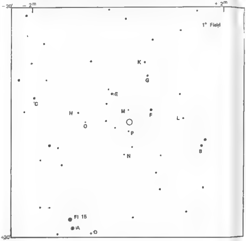


Comparison stars for 1° field

Star	Magnitude	Star	Magnitude
o	9·49	u	11·79
5	9·82	22	12·20
7	10·29	27	12·63
15	10·66	31	13·07
16	11·10	34	13·53
20	11·36		

R Trianguli

is a long-period variable with an extreme range of 5·4 to 12·0 magnitude and a mean period of 266 days.

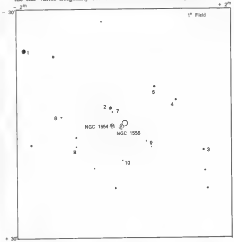


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude	Star	Magnitude
Fl 15 Tri	5·6	D	9·2	H	10·6	N	12·1
A	6·7	E	9·5	K	11·0	O	12·5
B	8·0	F	9·8	L	11·3	P	12·7
C	8·4	G	10·2	M	11·6		

T Tauri

is the prototype star of this group of nebular variables and may be located from its proximity to the small nebula NGC 1555. The extreme range is 9·5 to 13·0 magnitude but for the most part the star varies irregularly between tenth and eleventh magnitude.

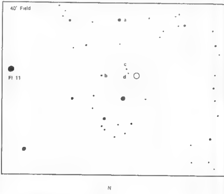


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude
1	7·8	5	10·0	8	11·2
2	8·3	6	10·2	9	11·6
3	9·1	7	10·8	10	12·1
4	9·5				

EV Lacertae

is a flare star with a normal brightness of 10·25 magnitude. The flares, which are usually quite infrequent, have an amplitude of about 0·5 magnitude.

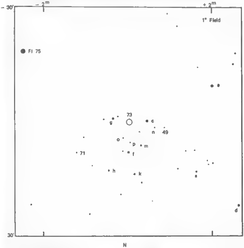


Comparison stars

Star	Magnitude	Star	Magnitude
a	8·45	d	10·79
b	9·21	companion	12·00
c	9·92	(EV + comp)	10·05

SS Cygni

is the brightest of all the U Geminorum stars with a range of 8·1 to 12·1 magnitude. The mean cycle is 50·39 days but individual cycle lengths may be anything from 30 to 70 days in length.

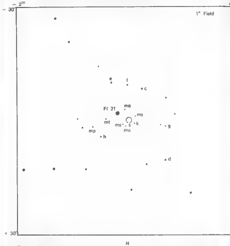


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude	Star	Magnitude
a	8·00	f	9·39	m	10·90	p	12·14
c	8·50	g	9·62	49	11·30	71	12·5
d	8·60	h	9·98	n	11·32	73	13·0
e	8·90	k	10·43	o	11·77		

X Leonis

is also a U Geminorum variable with a range of 12·0 to 15·2 magnitude and a mean cycle of 22 days.

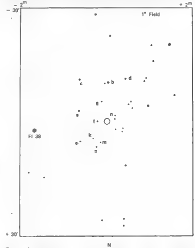


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude
c	11·25	h	12·9	mr	14·5
d	11·40	s	13·2	ms	14·7
e	11·76	k	13·5	mt	14·9
f	12·26	mq	13·9	mu	15·1
g	12·8				

RX Andromedae

is a member of the small Z Camelopardalis subgroup of the dwarf novae. The extreme range is 10·3 to 13·6 magnitude. During standstills it usually fluctuates around eleventh magnitude and there may also be periods of completely erratic behaviour.

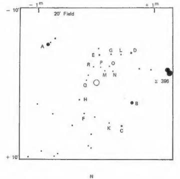


Comparison stars

Star	Magnitude	Star	Magnitude	Star	Magnitude
a	10·4	e	11·3	k	13·3
b	10·4	f	11·8	m	13·9
c	10·7	g	12·1	n	14·3
d	10·9	h	12·7		

AF Camelopardalis

is one of the fainter U Geminorum variables and has a range of 12·3 to 16·0 magnitude with a mean period of about 22 days. Very little is known of its behaviour at minimum owing to its faintness and more observations of this star are urgently required.



Comparison stars

Star	Magnitude	Star	Magnitude
A	9·6	K	13·7
B	10·1	L	13·9
C	12·4	M	14·0
D	12·5	N	14·3
E	12·7	O	14·7
F	13·0	P	15·5
G	13·5	Q	15·5
H	13·7	R	15·8

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1972 YEAR BOOK OF ASTRONOMY

Edited by Patrick Moore

The 1972 Yearbook follows the popular pattern of previous editions and amateur astronomers will find a wealth of information on every aspect of the stars and planets during 1972. Patrick Moore himself has contributed an article on southern stars and has, as usual, reviewed recent astronomical developments. Dr Porter has also contributed his invaluable notes for the year, together with his star charts, and information about eclipses, occultations, comets and meteors.

There are also articles about the far side of the moon, particular galaxies and quasars, modern infra-red astronomy and fireballs.

The Variable Star Observer's Handbook John Glasby

Sidgwick & Jackson